



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**MULTIPLE ASSETS POSITION DETERMINATION
IN A 3-DIMENSIONAL ENVIRONMENT
USING THE APRS PROTOCOL**

by

Evangelos K. Foutzitzis

September 2007

Thesis Advisor:

Andrew A. Parker

Second Reader:

James F. Ehlert

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**MULTIPLE ASSETS POSITION DETERMINATION IN A 3-DIMENSIONAL
ENVIRONMENT USING THE APRS PROTOCOL**

Evangelos Foutzitzis
Major, Hellenic Air Force
B.S., Hellenic Air Force Academy, 1992

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requirements for the degree of

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September 2007**

Author: Evangelos K. Foutzitzis

Approved by: Andrew A. Parker
Thesis Advisor

James F. Ehlert
Second Reader

Dan Boger
Chairman, Graduate School of Operations and Information
Sciences

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ABSTRACT

Increased situational awareness in the battlefield is one of the main objectives in today's operations and applies to all levels of commands. Several attempts have been made to use tracking devices for detecting and continuously updating the positional data of friendly assets on a map. Current applications like Falcon View fulfill their objective in presenting the location of targets of interest on a digital mapping environment. Falcon View is a geographic information system (GIS) used extensively by DoD for mission planning purposes. When the requirement is to track airborne assets such as aircraft or unmanned aerial vehicles (UAVs), none of the current applications can present the results in three-dimensions. Instead they project the received tracks on the ground in 2-dimensions creating a false or impaired perspective of the true tactical situation.

This thesis develops and tests a software application in a plug-in form integrated into the open-source NASA World Wind mapping engine. The application is designed to determine the tracks of both airborne and ground-moving assets in three dimensions. It also tests the concept in a real-world environment and verifies the impact it has on situational awareness at various command levels.

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EXECUTIVE SUMMARY

Increased situational awareness in the battlefield is one of the main objectives in today's operations and applies to all levels of commands. Several attempts have been made to use tracking devices for detecting and continuously updating the positional data of friendly assets on a map. Current applications like Falcon View fulfill their objective in presenting the location of targets of interest on a digital mapping environment. Falcon View is a geographic information system (GIS) used extensively by DoD for mission planning purposes. When the requirement is to track airborne assets such as aircraft or unmanned aerial vehicles (UAVs), none of the current applications can present the results in three-dimensions. Instead they project the received tracks on the ground in 2-dimensions creating a false or impaired perspective of the true tactical situation.

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I. INTRODUCTION

A. BACKGROUND

The Automatic Packet Reporting System (APRSTM) was developed in the early 1990s by Bob Bruninga, a contractor at the U.S. Naval Academy in Annapolis, Maryland, to support tracking of U. S. Naval Academy GPS-equipped boats in local waterways. The Automatic Position Reporting System is a software suite that provides fast and reliable communications between multiple nodes exchanging positional data in real time and with great accuracy. The basic concept of the software is that each station with new information will transmit positional updates to all the network's participating nodes. Once it is received, the information will be displayed as an update on a reference-system map. The APRS approach uses a one-to-many protocol to update the participating nodes with standard data formats, such as Mic-E, which have been developed to optimize the transmissions. By adapting these standard formats, users of different systems are able to observe local or remote traffic in a consistent manner, independent of the hardware or software used.

Although the APRS was created as a local data network, in the mid 1990s, its usage expanded when it was adopted by the worldwide amateur radio community. Digipeaters (simplex data repeaters) were established to relay the positional data beyond the originators' radio footprint. More recently through Internet interfaces, the APRS network's coverage was extended globally. The low-cost bandwidth of the Internet was used, resulting in a point-to-point or point-to-multipoint exchange of positional data among nodes spatially separated by several thousand miles. Today, any two APRS users, located anywhere on the planet with Internet conductivity, can exchange positional data and other information in near real time.

As the APRS capabilities matured, NASA released an open-source mapping software called NASA World Wind. NASA World Wind is a database for various scientific data that is used by NASA for mission planning requirements and by agencies in the fields of education, scientific research, government activities, and other public

interest issues. The flexibility of this application relies on software customization to fit the individual needs of a user, a feature provided by the open-source format.

World Wind permits users to zoom in on any location on the planet, providing high-resolution satellite imagery and Shuttle Radar Topography Mission (SRTM) elevation data. The result is a three-dimensional (3D) topographic environment rich in detail and highly accurate. World Wind provides a combination of non-commercialized data from multiple sources:

- Blue Marble – a medium-resolution full-color representation of the Earth as seen from orbital telescopes.
- Land Sat 7 – very high resolution imagery that exposes details such as roads, cars, and various man-made installations.
- Shuttle Radar Topography Mission (SRTM) – elevation data provided by satellites that scan the surface of the earth. This data, combined with the imagery, is used to create 3D representation of mountains, valleys, and other terrain features.

The release of open-source NASA World Wind provides new options for remote monitoring and tracking of APRS stations, since its detail-rich environment can be used to superimpose the position of an asset (including the altitude) with an extremely realistic representation.

B. THESIS OVERVIEW

1. Purpose

The objective of this thesis is to combine and test the capabilities of the APRS trackers used today by the amateur radio community with the 3D terrain features of mapping software like NASAs World Wind so the user will be able to visualize the tracking plots in a rich, detailed, and accurate environment. This presentation is expected to significantly increase the user's tactical situational awareness.

2. Scope

To support these objectives, an APRS network was developed to provide:

- a self-organized multi-node communications system that was then integrated to support the rapid, reliable exchange of information for local- and wide-area tactical, real-time events on radio and Internet networks.
- the ability to monitor and track friendly assets and to forward positional data to remote commands.
- a mapping engine capable of interpreting the received data in three dimensions, thereby increasing the situational awareness when used in conjunction with aerial assets.
- operations in environments where the Internet is not available.

C. THESIS STRUCTURE: OUTLINE OF CHAPTERS

Chapter I provides a brief background for our research and development of an APRS-based network combined with the NASA World Wind mapping engine used in numerous military and civilian applications. The chapter describes the nature of the research and the main purpose of the thesis.

Chapter II describes the fundamental components that comprise an APRS tracker and the procedures followed in building the various trackers used for collecting data.

Chapter III discusses the characteristics of the NASA World Wind software engine used today by the scientific community and provides the techniques used for interpolating the APRS-received positional data within the NASA World Wind mapping environment.

Chapter IV presents various APRS network attributes, such as encryption, and estimated costs for building a basic network and topology.

Chapter V describes the procedures and objectives for real-world testing of the software and hardware. The results of this testing are also analyzed.

Chapter VI provides various applications for the network.

Chapter VII presents conclusions based on the results of the experimental data-collection and considers initiatives for future implementation. The appendices show all the detailed supporting metrics from the individual experiments.

II. HARDWARE COMPONENTS

The APRS devices that are currently available have a small physical footprint both in size and in weight and can be carried by numerous assets, such as small unmanned aerial vehicles (UAVs) and personnel, without displacing other already integrated equipment. The functionality of these devices is oriented toward transmitting positional and other user-defined data such as equipment metrics, telemetry data, and identification attributes.

The user can define parameters such as transmission rates (when and how often the devices will transmit), call signs and the distance to be covered (from a few to hundreds of kilometers). Carrier Sense Multiple Access with Collision Detection (CSMA/CD) algorithms are used to avoid packet collisions, allowing multiple units to use the same channel. The theory of operation is that the GPS National Marine Electronics Association (NMEA) data sentences are reduced in size by discarding data deemed nonessential. Examples of this nonessential data are the dilution of precision data or the number of satellites in view. The remaining data is then compressed by using the standard APRS format. This results in a sentence of just a few bytes that is modulated on an analog signal and transmitted via a UHF or VHF channel. The result is low data-rate information that can be carried by limited bandwidth frequencies (UHF or VHF), potentially achieving great distances for airborne assets:

Raw GPS NMEA sentence

*\$GPGGA,170834,4124.8963,N,08151.6838,W,1,05,1.5,280.2,M,-34.0,M,,*75*

Raw GPS sentence with call sign

KI6EIT>:\$GPGGA,052421.00,4525.8693,N,12244.1256,W,1,06,1.54,00105,M,-019

APRS sentence

*KI6EIT>:!3542.94N/12045.85W/*A=00266*

APRS mic-E sentence

KI6EIT>:`0Iim]?K\>"6s}

A raw NMEA sentence is the data that a conventional GPS receiver provides in order to describe the GPS unit's location with reference to the whole world. An explanation of each field of the raw GPS-NMEA sentence presented is provided in the following section.

An APRS unit uses the amateur radio Packet protocols AX-25. The GPS receiver's digital data is converted into two distinctive frequency tones (binary 1 is represented by a 1200 Hz tone; binary 0 is represented by a 2200 Hz tone). Then they are forwarded to the microphone input of a handheld or mobile radio and are transmitted as a binary frequency shift keying (BFSK) signal to the receiving stations. On the receiving end, demodulated data from the radio receiver is passed to the radio modem and is converted back to a digital data stream and decoded. The reconstructed data sentences are used to determine the location of the transmitting stations on the mapping system as we see in Figure 1. In many parts of the world, digipeaters are used to relay the signals further. Most of them are connected with Internet servers (I-Gates) in order to merge the data into the World Wide Web. Several web sites, for example, APRS World and Findu.com, have been developed so users can access these positional data and observe the APRS traffic in real time.

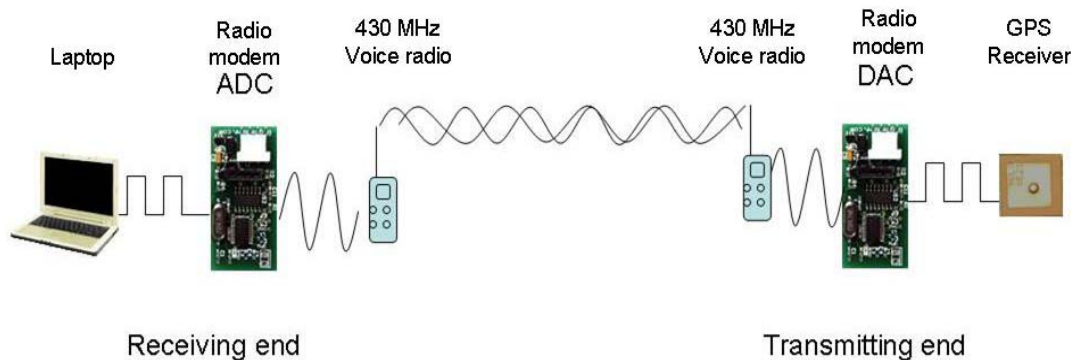


Figure 1. GPS position digital data radio link.

An APRS unit consists of:

- a GPS receiver
- a radio modem module, and
- a radio module.

Some devices act as a transmitter only, while others can also receive and/or repeat the received signal.

A. THE GPS COMPONENT

Any conventional GPS unit that exports data in the NMEA format can be used to parse the required positional data. Figures 2 and 3 show the two most common NMEA sentences that can be used for APRS purposes.

1. NMEA GPGGA Sentence

GGA - essential fix data which provide 3D location and accuracy data.

\$GPGGA,123519,4807.038,N,01131.000,E,1,08,0.9,545.4,M,46.9,M,,*47

Where:

| | |
|---------------|--|
| GGA | Global Positioning System Fix Data |
| 123519 | Fix taken at 12:35:19 UTC |
| 4807.038,N | Latitude 48 deg 07.038' N |
| 01131.000,E | Longitude 11 deg 31.000' E |
| 1 | Fix quality: 0 = invalid 1 = GPS fix (SPS) 2 = DGPS fix 3 = PPS fix 4 = Real Time Kinematic 5 = Float RTK 6 = estimated (dead reckoning) (2.3 feature) 7 = Manual input mode 8 = Simulation mode |
| 08 | Number of satellites being tracked |
| 0.9 | Horizontal dilution of position |
| 545.4,M | Altitude, Meters, above mean sea level |
| 46.9,M | Height of geoid (mean sea level) above WGS84 ellipsoid |
| (empty field) | Time in seconds since last DGPS update |
| (empty field) | DGPS station ID number |
| *47 | The checksum data, always begins with * |

Figure 2. GPGGA NMEA sentence structure attributes (From [1]).

2. NMEA GPRMC Sentence

\$GPRMC,123519,A,4807.038,N,01131.000,E,022.4,084.4,230394,003.1,W*6A
Where:

| | |
|-------------|---|
| RMC | Recommended Minimum sentence C |
| 123519 | Fix taken at 12:35:19 UTC |
| A | Status A=active or V=Void. |
| 4807.038,N | Latitude 48 deg 07.038' N |
| 01131.000,E | Longitude 11 deg 31.000' E |
| 022.4 | Speed over the ground in knots |
| 084.4 | Track angle in degrees True |
| 230394 | Date - 23rd of March 1994 |
| 003.1,W | Magnetic Variation |
| *6A | The checksum data, always begins with * |

Figure 3. GPRMC NMEA sentence structure attributes (From [1]).

B. RADIO MODEM COMPONENTS

1. Modem Settings

The purpose of the radio modem in an APRS transmitter system is to parse the GPS data, convert the data to APRS format, and forward the data sentence to the radio component for transmission. The modem can be set to trigger the radio in custom intervals (time, distance covered, or amount of degrees changed since the last position report). The radio modem can be programmed to key the radio only when needed to conserve the battery and also keep the frequency clear for monitoring the transmissions of other APRS stations.

These modem settings are independent of the frequency band selected and can be used for transmitting fixed positional data even without the use of an active GPS receiver. After setting the required modem operation parameters, the settings can be saved in the internal memory. The radio modems used for many APRS transmission use a Graphical User Interface (GUI) to set up the transmission parameters.

The image in Figure 4 is an example of the GUI that the TinyTrack radio modem uses.

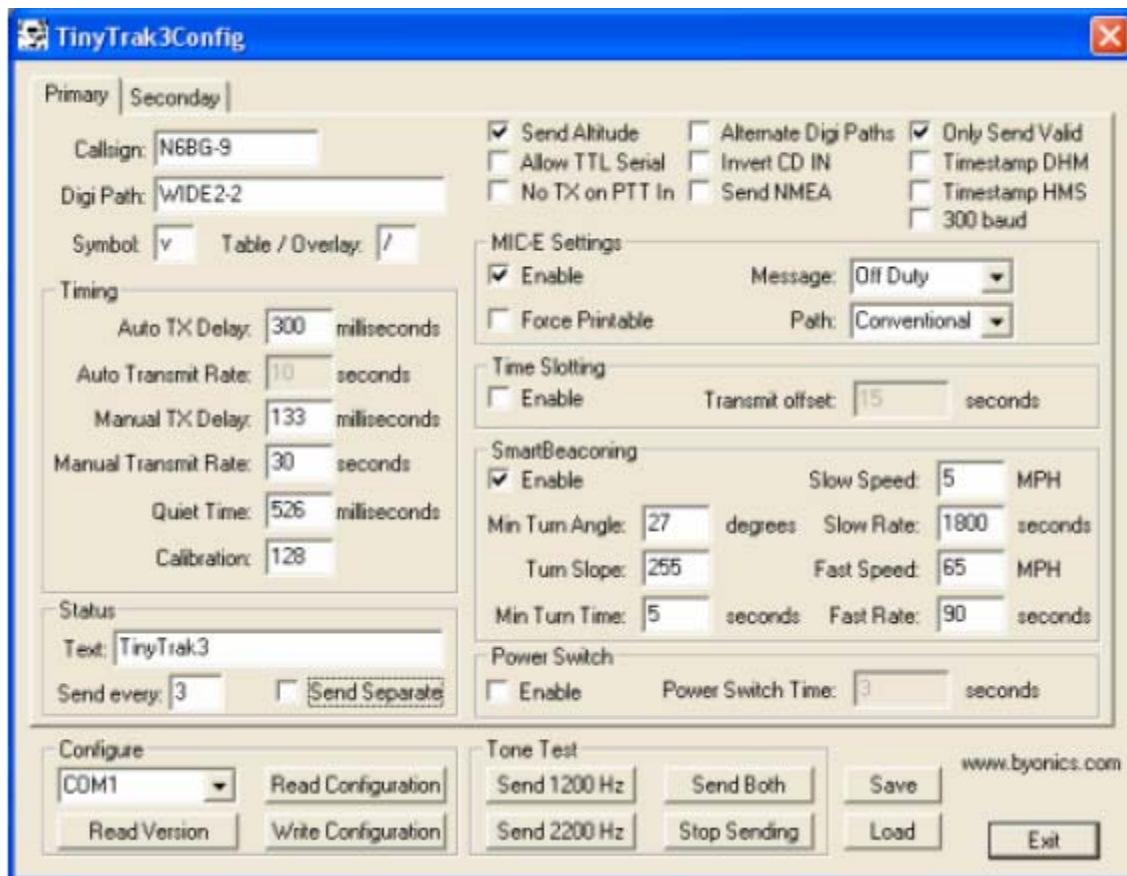


Figure 4. TinyTrack user interface (From [2]).

On this template you can set or change parameters such as call signs and transmit rates:

The Call Sign is the unique identifier of the APRS station. This field is typically populated by the amateur radio call sign assigned by the Federal Communications Commission (FCC) or country specific equivalent regulating body. Alternatively, a tactical call sign, such as BUS, can be used and can be accompanied by an optional service set identifier (SSID) between 1 and 15.

The Digi Path is the field to use when the data is to be relayed by signal repeaters (digipeaters). Up to 7 digipeaters can be used to achieve a maximum range, but specific rules must be followed to comply with regulations set by the FCC or equivalent governing body and the radio amateur community (described in the next section).

Figures 5 through 9 show the different topologies that the signals can be transmitted:

TRANSMISSION PATH

A) Omni directional

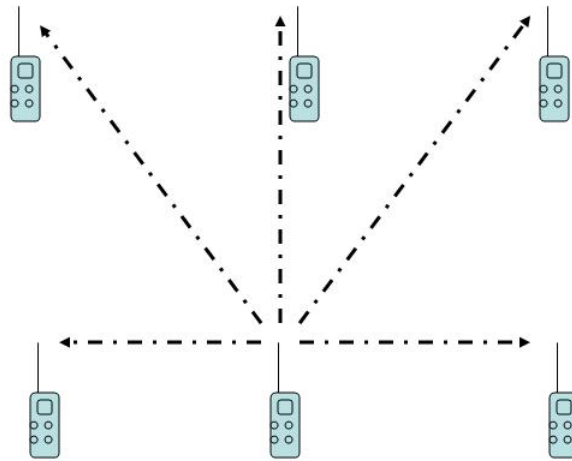


Figure 5. Omni-directional APRS reception.

TRANSMISSION PATH

B) Spatially defined

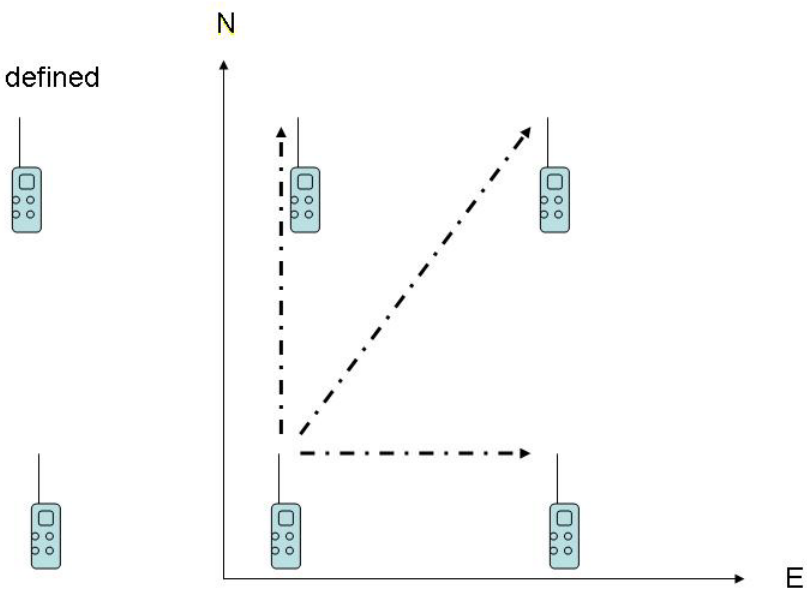


Figure 6. Sectorized APRS reception.

TRANSMISSION PATH

C) Specific route

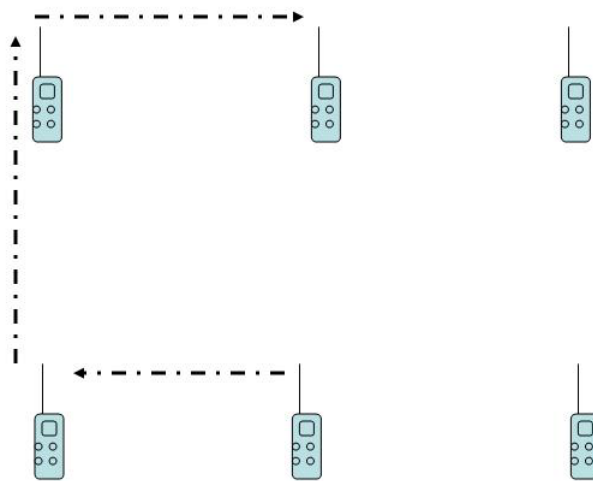


Figure 7. APRS data-routing capability.

TRANSMISSION PATH

D) RF to internet / Network

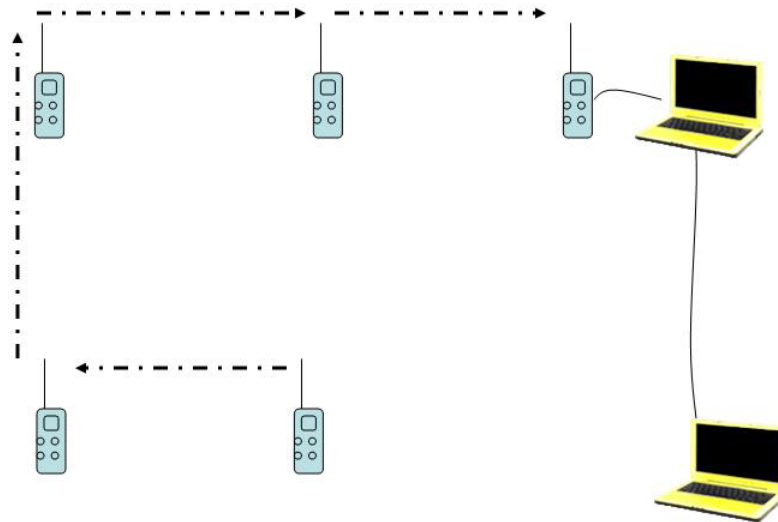


Figure 8. Remote distribution of APRS data through I-Gates.

TRANSMISSION PATH

Controlled # hops = Controlled Range

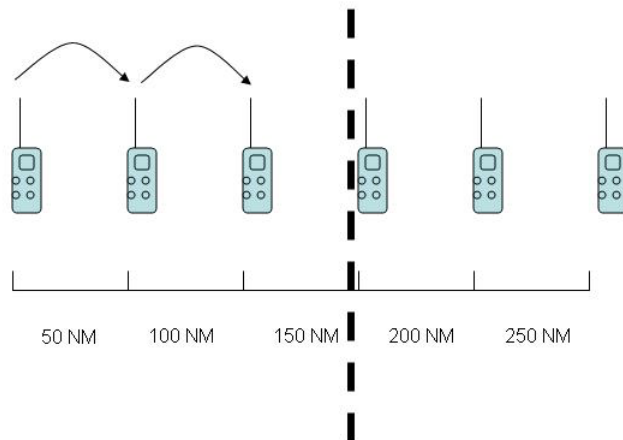


Figure 9. APRS-controlled range coverage.

If the signal is to be received and retransmitted from specific digipeaters, we use their call signs in the corresponding field. By doing so, our transmissions can be controlled in terms of spatial distribution: where and how far the transmission will go.

2. Digipeaters

Digipeaters are the facilities that relay the received APRS signals and extend the range of the information normally limited by the source's VHF footprint. Digipeaters operate like simplex voice repeaters, but they relay digital data. An APRS packet should contain the name of the repeater in its structure otherwise it will not be repeated by that particular station. APRS packets can be digipeated up to seven times, but will not be forwarded any further in an effort to reduce the data traffic and avoid packet collisions. To relay the signals, the APRS protocol uses general aliases such as RELAY and WIDE. Aliases are used when data is to be relayed, but the particular path or names (call signs) of the digipeaters are unknown. Corresponding digipeaters can retransmit only packets that contain a corresponding alias, for example, RELAY or WIDE. The main difference between RELAY and WIDE digipeaters is their power output and the range they cover. A RELAY digipeater, a low-level digipeter, will receive and retransmit the signal of an APRS station only a few miles, until it is received by a higher-power, high-level digipeter such as WIDE and relayed typically up to 50 miles.

C. RADIO COMPONENTS

Several types of radios can be used to transmit APRS data. The most common types use VHF/UHF-frequency ranges because of the unique characteristics of their wavelengths and their availability to the amateur radio consumer market. The purpose of an APRS radio is to receive and transmit BFSK data in concert with the radio's modem over a particular VHF or UHF channel. The standard APRS BFSK data rate is 1200 baud, with tone frequencies of 1200 Hz and 2200 Hz for mark and space, respectively.

D. APRS TRANSMITTER ASSEMBLY

The radios used in the experiments described here were a YAESU VX-7R and a KENWOOD TH-7D. The KENWOOD radio has an integrated radio modem that simplifies the transmission of APRS-packets, since the only component missing to complete the system is a GPS receiver. The two APRS transmitters used as network nodes were a BeeLine 20 mW transceiver and a 300 mW ELCOM personal tracker.

Eight experiments were conducted at facilities at Camp Roberts and Fort Hunter Liggett to determine the network coverage both with and without the use of repeaters. The results are presented in the following chapters.

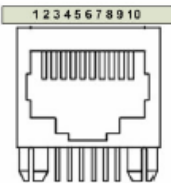
1. YAESU VX-7R Radio with an ELCOM Radio Modem



Figure 10. YAESU VX-7R radio and ELCOM radio combination (From [3], [4]).

The YAESU VX-7R is an excellent radio for APRS activities. Its small size and light weight are ideal for mobile operations, and, with a full 5 watts of transmitted power, it can increase dramatically the usable footprint of transmissions. We combined a VX-7R and an ELCOM radio modem to provide a small-footprint digipeater that could then be placed on a tethered balloon and also used as a ground receiving station. Figures 13 through 16 show these integration phases. To connect the radio with the radio modem, we used a CT-91 microphone adapter.

The 2.5mm and 3.5mm radio plugs used came from a local Radio Shack store. We made a connecting cable with CAT5 wire by first connecting the green and the white-purple wires together and then to the tip of a 2.5 mm plug. The ring of the 2.5mm plug was connected to the red wire of the CAT5 cable, the analog ground, which was connected to the ring of the 3.5mm plug. The black receive (RX) wire was connected to the tip of the 3.5mm plug. The orange wire was connected with the positive pole of a 9V, 1.2 A-hr battery, and the white-orange cable with the negative pole. Although ELCOM radio modems include an internal NiMH 110 mA-h 4.8 V battery, we found that it lasts for only two hours of continuous operations. So we replaced it with a readily available lithium polymer 1.2 A-hr, 9 V battery. Figure 11 is from the ELCOM user's manual.



| External Power Supply Part | | |
|----------------------------|----------------|----------------------|
| PIN 1 | ORANGE / WHITE | GPS and Supply GND |
| PIN 2 | ORANGE | EXT Supply VCC |
| Digital I/O or A/D pin | | |
| PIN 3 | GREEN / WHITE | I/O and A/D Pin |
| GPS NMEA-183 Part (RS232) | | |
| PIN 4 | BLUE | RS232 TX |
| PIN 5 | BLUE / WHITE | RS232 RX |
| Radio Connection Part | | |
| PIN 6 | GREEN | PTT handheld Radio |
| PIN 7 | WHITE / PURPLE | TX |
| PIN 8 | BROWN | PTT stationary Radio |
| PIN 9 | BLACK | RX |
| PIN 10 | RED | Analog GND (Radio) |

Figure 11. RJ11 version 2.0 pin-out and radio cable color codes (From [5]).

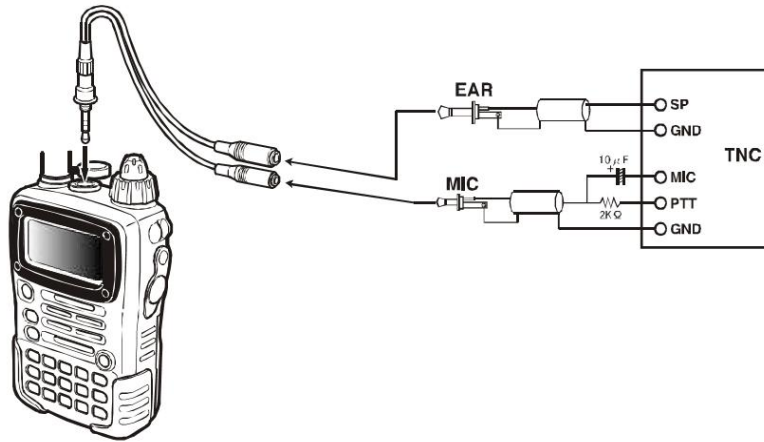


Figure 12. CABLE for a YAESU VX-7R and ELCOM radio modem (From [3]).

Below are illustrations of the integration.

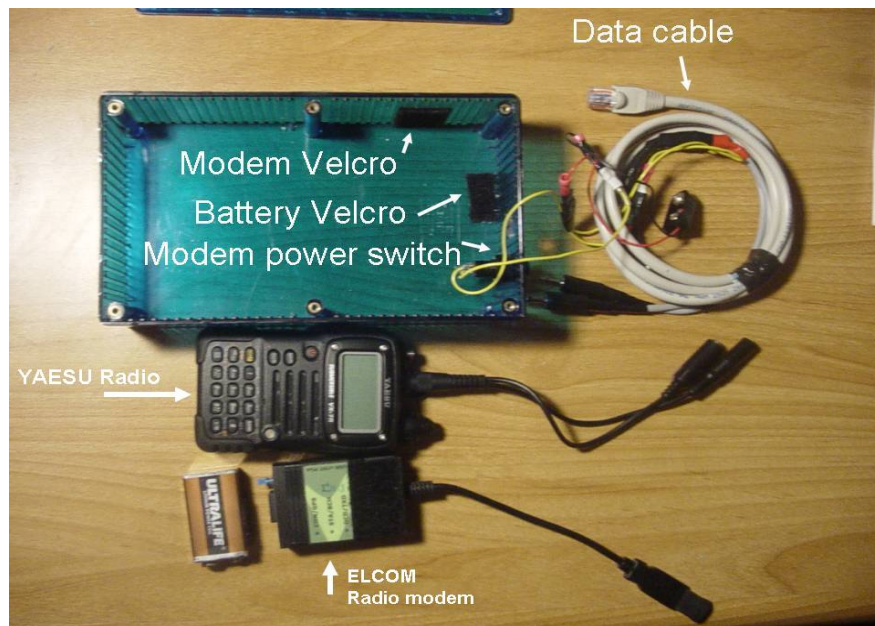


Figure 13. Components used to build the ELCOM digipeater.

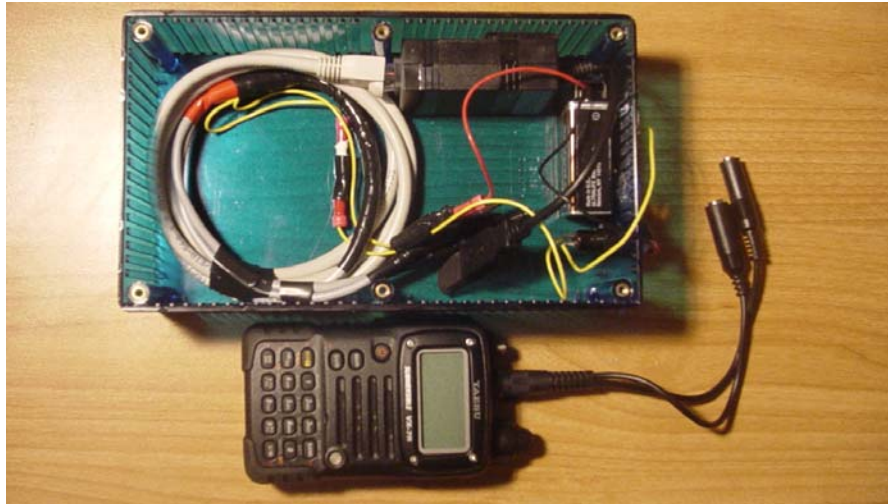


Figure 14. Placing the components inside the box.

The components were attached with Velcro inside the box to avoid their displacement when airborne.

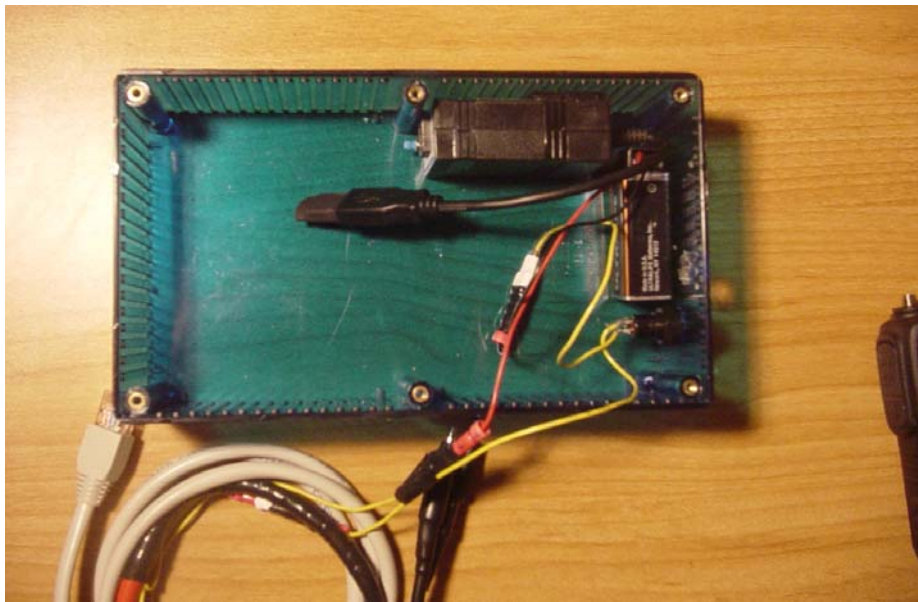


Figure 15. The 1.2 A-hr, 9 V battery provided operation for 8 hours.



Figure 16. Placing the antenna and the extension cable.

A Dremel stylus rotary tool was used to drill holes on the box for placing the antenna and the power switch.

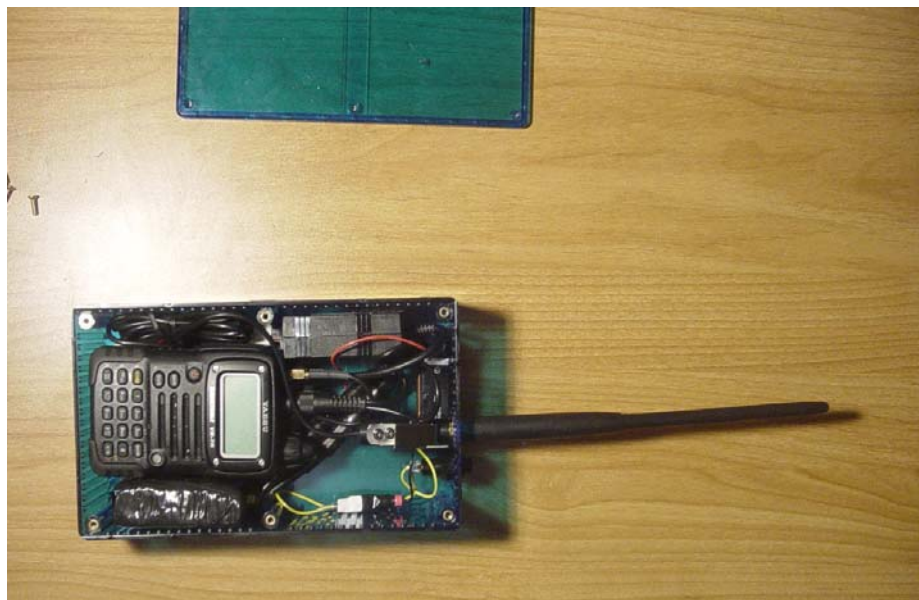


Figure 17. Final assembly.



Figure 18. Attaching the repeater to a 10-foot-helium filled balloon.

2. TH-7D KENWOOD and ForeTrex 201 GARMIN GPS [6]



Figure 19. Foretrex 201 GARMIN "Personal Navigator" Wrist GPS.

This section of the research is an excellent tutorial of how to build a robust APRS tracker in just a few steps. This tutorial (article and figures) created by Stephen H. Smith (WA8LMF), so it is presented as is without any modification.

The ForeTrex 201 GARMIN GPS receiver may well be the ultimate accessory for the KENWOOD TH-D7 APRS hand-held radio. The TH-D7 has a serial-data input jack for transmitting position reports provided by an attached GPS receiver. However, most GPS devices other than raw GPS receiver chips are nearly as conveniently portable as the KENWOOD radio.

The GARMIN ForeTrex 201™ “Personal Navigator” is a miniature GPS receiver that can be worn like a wristwatch. It is powered by an internal rechargeable lithium-ion battery that, according to the manual, will power the unit for up to 15 hours.

In addition to its own extensive data displays presented on a very legible LCD screen, the unit outputs NMEA 0183, 4800 baud 8-N-1 serial data through a 2.5mm stereo mini-jack. The ForeTrex works perfectly with the KENWOOD TH-D7 and D700 transceivers and with virtually all moving map programs running on PCs .

A built-in patch antenna is located in the area under the GARMIN logo. It is astonishingly sensitive. We found that it works quite consistently while walking with that arm by your side, with no special effort to orient the unit favorably toward the sky. It even works inside a car, as long as it is worn on the left hand while that hand is kept on the steering wheel.

The ForeTrex 201 is available from a variety of Internet websites at prices ranging from its list of \$179 to under \$130. When searching sites, be sure to look for the ForeTrex 201. Don’t confuse it with the less expensive ForeTrex 101, which lacks the rechargeable lithium battery and, instead, requires vast quantities of expensive non-rechargeable AAA alkaline cells. The 101 also has a much less usable serial port connector. Also avoid the similarly named ForeRunner series, which are oriented to athletics and physical training. While the ForeRunner series looks identical at first glance, it does not have the standard NMEA data output required by the KENWOOD and most computer programs.

With the ForeTrex, the external power and serial port are contact pads on the back. A separate “cradle,” that snaps onto the back of the unit, mates with the pads and provides a 2.5mm stereo mini-jack for data and a 1.7mm micro-miniature coax power jack for 5 VDC power input.



Figure 20. Connecting the GPS with a KENWOOD TH-7D radio.

The cradle is designed to be snapped onto the unit for charging while not being worn, but the ForeTrex is perfectly wearable with the cradle installed. The cradle adds about a ¼-inch of height to the 201. This unit comes with a 2.5mm stereo miniplug-to-DB9-female connector cable to connect the ForeTrex to a PC. The cable has a pin-out that is identical to the one used to program a TH-D7 or VC-H1 from a PC.

To use the unit with a KENWOOD TH-D7, use a 2.5mm-to-2.5mm stereo patch cord. Cut the cable in the center and cross the two hot conductors, TXD and RXD. Plug one end into the ForeTrex and the other into the GPS port of the TH-D7. Set the TH-D7

(or D700) APRS menu to use a GPS. In the GPS item of the APRS menu, choose “NMEA,” which means NMEA at 4800 baud. Do not select the alternate “NMEA 9600.” On the ForeTrex, navigate to the “Setup” menu and set the external port to NMEA (it defaults to GARMIN proprietary format). The baud rate is fixed at 4800.

When you press the “POS” button on the TH-D7 (once the ForeTrex has achieved GPS lock), you should see the same coordinates, truncated by one decimal place, as the ForeTrex display.

You can even use the tiny ForeTrex map display to show positions received from other stations by the TH-D7 (or D700). On the TH-D7, select menu 2-3 (“APRS,” “WAYPOINTS”) and choose “8 Digits NMEA.” This routes APRS position reports received by the TH-D7 (or D700 mobile) to be uploaded to the attached GPS as NMEA waypoints. The “8-digit” waypoint format causes waypoints to be labeled with the full call sign and SSID of the station: that is, WA6XYZ-9. You do not get a roadmap display like UIview or WinAPRS (unless, of course, you use a mapping GPS device like a Street Pilot or TomTom), but you can see the distance and direction of other stations relative to you in the center of the screen.

With ForeTrex firmware versions earlier than the 2.3, the device reverts to the GARMIN format every time the unit is switched off. With the firmware upgraded to 2.3 or higher (a self-installing upgrade in Windows is downloadable from the Garmin website), the unit remembers the NMEA mode setting.

The main connection issue is that, like the Radio Shack DigiTraveller GPS, the unit's serial port will not start talking until it sees a non-zero voltage on the data input pin. Any voltage, positive or negative, of more than about 1 volt on the input pin will turn the serial port on. In other words, you can not use a simple two-wire (TXD and GND/COMMON) hookup.

This presents no problem with either a PC or a TH-D7, both of which present a non-zero voltage (most PC ports are quiescent at -8 volts or so, while the TH-D7 presents +5 volts out). This *is* a problem, however, with the TinyTrak, since its data output line is set to zero volts during normal operation. Probably the simplest way to

handle the TinyTrak is to apply +5 volts from its internal regulator through a 1 k Ω resistor to the data input line of the ForeTrex. The very lightweight ForeTrex comes with an astonishingly heavy 5 VDC 500mA wall charger (apparently an old-fashioned analog 60Hz transformer design rather than the light-weight switch-mode power supplies provided with cell phones, digicams, and home routers. The measured current draw is about 120mA inrush when the batteries start charging. Once charged, the unit draws only about 40mA to operate.

A cable was constructed from an old PS/2 mouse cable to port 5VDC from my laptop external keyboard port and it works perfectly. This adaptor allows me to recharge or run the unit from the laptop's batteries or supply.

Figure 21 shows the custom cables. The cables combine power and data connections at the ForeTrex end and branch out to DB9 data and PS/2 power at the PC end. The biggest challenge in the assembly was finding a molded cable assembly with the micro-miniature coax DC power plug that mates with the ForeTrex. Both the DC power cable and the 2.5mm-to-2.5mm stereo patch cord are catalog items in the Philmore Electronics line of minor electronic parts. The coax power plug molded onto a 6' cable is Philmore part #48-410. We constructed a similar cable-to-port 5 VDC from a USB port. Standard USB ports can supply up to 500mA at 5 VDC to power devices plugged into them.



Figure 21. Power and data connections for the ForeTrex GPS receiver.

Finally, an incredibly useful add-on for the ForeTrex 201 is the free software utility, G7toWin. With this program, you can download waypoints, recorded tracks, and even the bitmap graphics screens from the ForeTrex to files on your PC. The program is downloadable from <http://www.gpsinformation.org/ronh/g7towin.htm>. Unlike many similar GPS utilities, it allows you to save the downloaded data into standard comma-separated .CSV files usable by practically any database, spreadsheet, or mapping program. It can even save the data directly into Delorme .SA8 overlay files, usable directly by Street Atlas, Topo USA, and others. Note that the serial port mode of the ForeTrex must be set to “GARMIN” rather than “NMEA” to use this program.

3. BeeLine GPS Transmitter

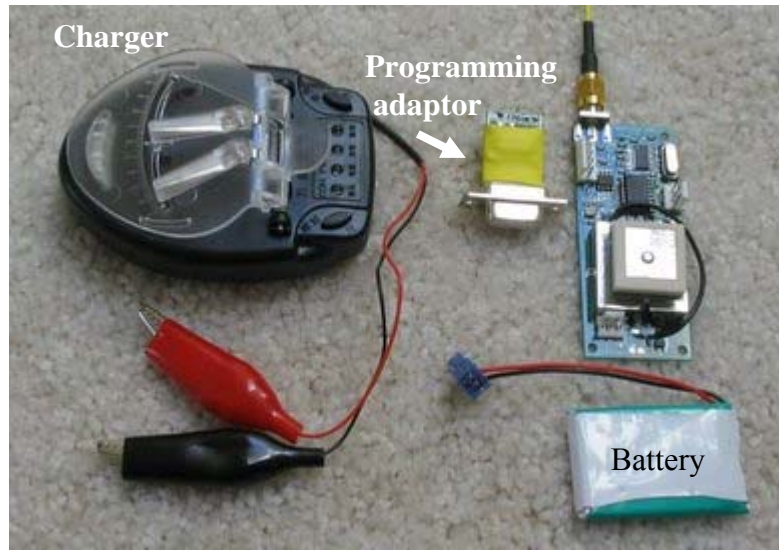


Figure 22. BeeLine GPS transmitter components (From [7]).

The BeeLine GPS transmitter is a combination of a UHF radio, a radio modem, and a GPS receiver. It is capable only of transmitting only, and can neither receive nor digipeat APRS messages. Its transmitting power spans from 12 dB (1-20mW). Despite its small size, long-range LOS transmissions at altitude can provide long coverage tracking. The Li-Po battery can provide operation for at least 8 hours with a transmission rate once every two seconds at a 20 mW power level. An integrated microcontroller parses the latitude, longitude, and altitude from the GPS receiver and converts them into an APRS format. This APRS format is subsequently modulated and forwarded to the radio module for transmission at 1200 baud rate. A suitable receiver and a packet decoder on the receiving end must be provided for plotting this data on a screen. Since it is only a transmitter, it cannot be used as is for multiple simultaneous transmissions from several devices on the same channel. This is due to potential packet collisions and data corruption.

The author of this thesis contacted the developer of this board, Greg Clark, and requested a time-slotting capability. Clark then sent a new firmware whereby multiple

transmitters could be synchronized in a single frequency. The idea behind our request was that the transmitters would use the GPS clock for synchronization, so each one would transmit on a predefined time slot.

The screenshot displays the BeeLine users interface, which is a web-based configuration tool for a transmitter. The interface is organized into several sections with input fields and control buttons.

- Top Section:** Includes a dropdown for 'COM port' (set to COM1), a 'Model' field (BLGPS0), and a 'Read' button. Below this are 'Frequency' (133.920 Mhz), 'Version' (22), and a 'Write' button. Further down are 'Output Power' (12 dBm), 'Battery' (4.14 V), and a 'Run' button.
- Configuration Section:** Contains 'Pkt Interval' (10 secs), 'Store Interval' (10 secs), 'Preamble' (10), and 'TimeSlot' (10). Below these are 'ID String' (K7RKT), 'SSID' (1), and 'Symbol' (-). There are several checkboxes: 'Enable Slotting' (unchecked), 'Enable APTS Packet Format' (checked), 'Position Logging On' (unchecked), 'Enable Course/Speed' (unchecked), 'Wrap Data Log' (unchecked), 'Smart Logging' (unchecked), and 'Disable RF out' (unchecked).
- Path and Frequency Section:** Includes 'Path' (WIDE1 1), 'WIDE2 1', and 'fcal' (-50).
- Low Voltage Section:** Includes 'Low V' (3.40), 'Low V shutdown enable' (checked), 'Ser#' (7), and an 'Update' button.
- Messages Section:** Includes a 'Messages' field showing 'time: vch:2 vcl: 44 t2:0 t1:0 t0:0' and a 'Clear Flash' button.
- Bottom Section:** Includes a 'Time' field (0:00:00), a 'COM Port Timeout (secs)' field (3), and a 'Read Flash' button.

Figure 23. BeeLine users interface with the addition of time-slotting (From [8]).

III. SOFTWARE COMPONENTS

A. NASA WORLD WIND

We used the NASA World Wind 3D software engine as a plotting platform to interpret the received data on the 3D terrain map. To aid the decision-making process, we also developed several tools, such as reference grids, Bullseyes, and conversions among coordinate systems. The tools create a common reference system, so multiple users can work in the same environment at the same time. The NASA World Wind is an open-source application: everyone has access to the source code and it is free. World Wind provides a 3D environment within which a wide variety of data sets can be viewed with highly accurate representation of the Earth as a context. Through its user-friendly interface, the entire planet can be navigated in 3D, all the way from satellite altitudes down to a single desired geographic location.

World Wind uses satellite imagery from various NASA missions as well as aerial imagery. The images are geo-rectified and geo-referenced, so they provide the most accurate and detailed mapping system available to the public. Several ground resolutions are provided, from 1km per pixel up to 15m per pixel.

World Wind also allows the use of external imagery databases, so privately owned or classified data can be incorporated with ease. For example, during one test we purchased data from a civilian satellite-image provider that included a picture of Thailand in which the ground resolution was 60 cm per pixel.

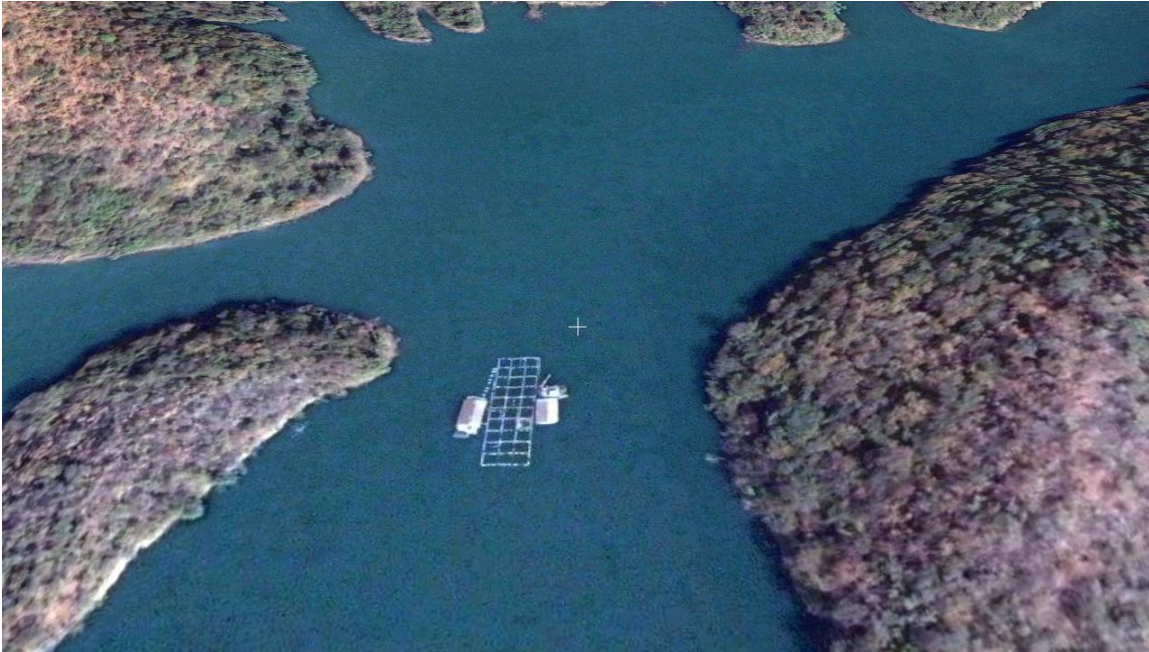


Figure 24. Boathouse in Mae Gnad, Thailand: 60 cm per pixel ground resolution.

As a user zooms in from higher altitudes toward the surface of the earth, World Wind transitions to higher-resolution imagery datasets, so an increasing amount of detail is revealed. Additionally, data from the Shuttle Radar Topography Mission (SRTM) are also used, which provides elevation data across the entire planet in several resolutions. The latest elevation data came from an eleven-day mission and was collected by the Space Shuttle Endeavor in February 2000. Like imagery datasets, more detailed, privately owned elevation data can also be imported into World Wind to increase the 3D detail.

By combining the increased resolution images with very detailed elevation data, we get a 3D representation of the earth that allows us to navigate anywhere on the planet. User-friendly controls with mouse buttons are used to control the camera point-of-view and desired locations during our navigation on the Earth's surface.

Data Layers

World Wind's core is built in a way that allows concurrent representations of several information layers or overlays apart from the imagery ones. For example, plot

place names, boundary and country border lines, and weather data can be plotted, along with other shape files that are widely and publicly available.

Networking ability

NASAs application uses the Internet to connect to remote servers and download required data – images or other information – via an extendable markup language (XML) template. As a user zooms into a specific location, a query is passed to NASAs (or other privately owned) servers, so the use of bandwidth is limited each time to only the data needed. The user has the option of adjusting the cache memory of the application to save the downloaded datasets for off-line viewing. Thus, limitless datasets can be added any time more information or details are needed. The add-on architecture of World Wind also allows third parties to create their own individual data sets and to share them with other users. To date, several organizations have published their privately owned data sets, thereby expanding World Wind’s capabilities.

Plug-ins

Because World Wind uses a plug-in architecture, new features and capabilities can be imported. The open-source community has contributed a lot in this direction, which has resulted in the creation of several new features and functions. World Wind is written in C-sharp (C#), Microsoft’s Net Framework, thus allowing the use of open-standards formats, such as Extensible Markup Language (XML). Also, it uses Microsoft’s DirectX architecture to represent the 3D characteristics of the plotted objects. Recently, a new effort began to migrate to a Java version of World Wind, so it would be available to a wider community of programmers and developers.

To add data of new functionality to World Wind, you must follow a two-step process. First, create the additional data. Then, reference the location of the data by creating an XML file.

B. GPSTRACKER PLUG-IN INTERFACE

The following section describes the process developed by this thesis author and Javier Santoro, a Canada-based programmer, for adding the APRS received data to the World Wind environment. The thesis author's contribution to the software part included the development of the concept of a 3D interpolation of APRS sources into NASA World Wind and the provision of the specifications of the APRS format to Javier Santoro so that he could compile the necessary code for this integration. The author of this thesis and Javier Santoro started this integration in January 2006 by exchanging specifications and code, debugging and testing the results on a daily base. New formats were added (such as mic-E) that more efficiently used the RF spectrum for low data rate transmissions.

World Wind exports an Application Programming Interface (API) that allows third-party developers to write software-component, dynamic-link libraries (dll's) that can interact with World Wind. Everything that can be displayed in the WW window belongs to a layer. Plug-ins are able to display icons, lines, and other graphics, on top of the world by creating layers. GPSTracker is a World Wind plug-in that has three main components:

- The interface to World Wind. This component is in charge of creating, adding, modifying, and displaying layers (a layer may display the icon of a source been tracked, a shape file, a track line, and other graphics.).
- The user interface component is in charge of displaying and handling the GPSTracker configuration window that users use to set up all the different sources and settings.
- The GPS data-receiving, -parsing, and -exporting component. This component is in charge of getting GPS data from all supported sources (COM, TCP, UDP, and files.), parsing the information to a GPSTracker-known format, and sending this information to I/O component. This component is also in charge of exporting the information to different formats (a file, a UDP port, an external control, an HTTP server).

More specifically, the three components work as follows.

1. Layers Component

World Wind exports the plug-in class, `WorldWind.PluginEngine.Plugin`. GPSTracker creates a class that is based on the plug-in class, `public class GpsTrackerPlugin: WorldWind.PluginEngine.Plugin`. When World Wind boots up, it looks under the Plug-in directory for dlls that implement a class derived from the plug-in class. Every time a dll is found it is loaded into World Wind, thereby effectively becoming part of World Wind. When the GPSTracker Plug-in is loaded and initiated, it adds the GPSTracker icon to the WW toolbar and creates an instance of the class `GPSTracker: public class GPSTracker: System.Windows.Forms.Form`. The GPSTracker class is based on the C# Form class and is the one that implements the user interface. GPSTracker plug-in also creates the main GPSTracker layer that shows up in the layer manager under the name GPSTracker. All subsequent layers (for tracked sources icons, POI.) are created by GPSTracker Plug-in as sub-layers of the main GPSTracker plug-in layer. When the I/O component sends information about a source been tracked to this component, if it's the first time, the GPSTracker plug-in creates a new layer for that source and displays the appropriate graphic shape at the appropriate position (depending on whether it's a source, Point-of-interest, or other file). World Wind will keep calling into the GPSTracker plug-in layers to keep displaying the layers.

2. User Interface Component

The user interface window is divided into two main parts:

The sources tree. Under this tree the user can add and track up to a max of 512 sources. Each source may get the GPS data from any of the supported transports (COM, TCP, UDP, and file).

The source configuration panel. This panel is made up of tabs by which the user can configure the selected source from the tree, such as the COM or TCP settings. Once all the sources have been configured, the user clicks on track and the I/O component starts.

3. I/O Component

This component works basically the same way for every type of source. For every configured source a new thread is created that listens on the source's configured transport (the selected COM port for a COM source; the selected IP address/port for a TCP port). Every time a message comes into that connection, the message is parsed to see if it's one of the supported formats (GPSTracker supports two main formats: NMEA and APRS). If the message can be decoded, the information is set to a layers component to be displayed.

Below is an image representing various sources being plotted on World Wind Environment through the GPSTracker plug-in.

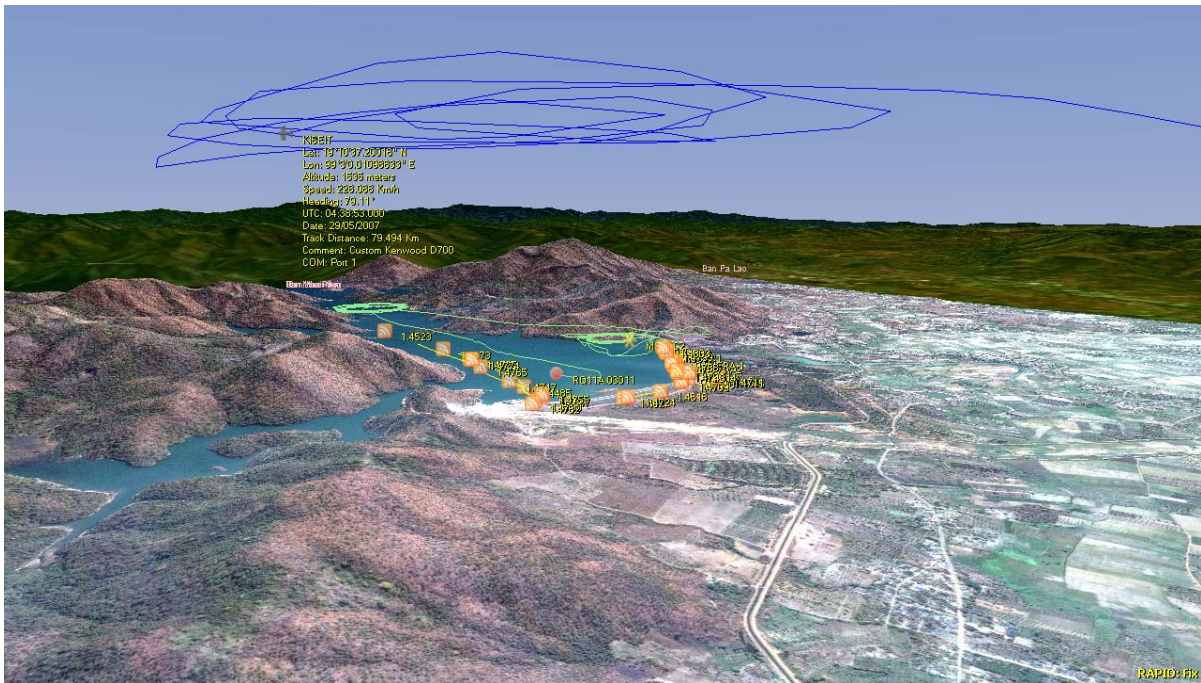


Figure 25. Multiple assets position determination on NASAs World Wind.

C. APRS FORMATS USED

1. Standard APRS

Most APRS software decoders can recognize the standard APRS format (below):

```
KI6EIT>APRS:$PRWIZCH,04,7,05,7,00,0,21,0,00,0,30,7,06,7,13,2,10,7,02,7,00,0,00,0*49
```

```
KI6EIT>>APRS:$GPRMC,145322,A,4034.3765,N,10410.8083,W,12.062,220.7,220406,9.9,E*56
```

```
KI6EIT>>APRS:$GPGGA,145324,4034.3714,N,10410.8151,W,1,06,1.46,21869.4,M,-22.1,M,,*47
```

2. MIC-E

The mic-E format is one of the most popular formats used in APRS networks:

```
KI6EIT>:0KH_?2#\ "3r}
```

Many users prefer this format largely because of its short sentence, which optimizes the over-the-air transmission and thus reduces both network traffic and packet collisions. However, a drawback of the mic-E format is that it doesn't use a timestamp. While this is fine for most amateur radio applications, for military applications and our thesis experiments, the format lacks a crucial ability: the ability to replay received positional data and re-create the tracks in a timely manner. In our case, the solution was to append the receiving station's (computer) timestamp to the received packets. A very accurate time-server was used to synchronize the computer's clock with the time-server's clock, the timestamp was then added to the mic-E sentence, and the problem was solved. In the process, the sentence becomes much longer,

```
KI6EIT>:0KH_?2#\ "3r}->APRSMSTIME:17-7-2007-19-44-53
```

but the network speed is not affected, because the manipulation takes place inside the receiving application (software) and is not transmitted over the air.

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IV. NETWORK ATTRIBUTES

A. NETWORK TOPOLOGY

Point-to-point and point-to-multipoint links can be established with selective availability to the users. For example, the transmission routes or data to be received from specific nodes can be specified, thereby assuring the reception of only the essential data each time. Several isolated and spatially separated networks are combined to form a large-scale monitoring net that forwards the data to multiple recipients inside or outside the network. Each isolated network is characterized by increased mobility, a small and light-weight footprint and long-range coverage.

B. ENCRYPTION

The Advanced Encryption Standard (AES) 256 encryption scheme, the APRS format compression/encryption, and the low transmission power all work together to minimize third-party interception and exploitation. The AES 256 encryption is a high-level cipher algorithm that uses a broad range of block and key sizes.

C. COST

The development budget for an APRS network is low, because the building blocks are off-the-shelf components and the functionality lies behind the data manipulation. Table 1 presents the typical budget needed for building a small scale APRS network.

| | |
|---|---------|
| YAESU VX-7R | \$ 360 |
| ELCOM Radio modem | \$ 128 |
| BeeLine GPS | \$ 249 |
| KENWOOD TH-D7 | \$ 330 |
| Cables, connectors, batteries, switches | \$ 50 |
| Total | \$ 1117 |

Table 1. Average budget for a small scale APRS network.

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V. TESTS AND METRICS

Several experiments were conducted at Camp Roberts and Fort Hunter Liggett in central California in conjunction with the Cooperative Operations and Applied Science & Technology Studies (COAST 2007) field experimentation program. The results are being presented as after-action reports.

The main objectives of Test I-V were to define a radius from the base station (C2) using an airborne repeater, so the APRS network would be always functional and independent of environmental and physical obstructions like mountains. Various APRS transmitters were tested and their performance measured in terms of their maximum transmitting distance. To achieve this, a tethered balloon was launched so that the nodes would always have a line-of-sight (LOS) between them. A repeater was placed on the balloon and the balloon relayed the signal at the tethered point (ground station) directly below the balloon. Thus, the distances measured were actual LOS distances. The equipment used for this experiment was:

- Balloon repeater: A 5-watt YAESU VX-7R handheld radio, connected with an ELCOMs micro uTNTTM radio modem, in digipeating mode.

| | |
|--|---|
| Dimensions | 7 x 2 x 4 inches (w/o antenna) |
| Weight | 1 pound |
| Crew | Autonomous Operator |
| Max Range | Depending of the platform altitude. An average <u>radius</u> of 60 Km with the balloon @ 5500' was measured. With the proper antenna (~3 dBi) the range will be almost doubled. (Test 2 objectives). |
| Endurance | 12 Hours of continuous operation was measured with a single lithium polymer 9V battery And transmissions every 12 seconds. |
| Power | Lithium Polymer 9V battery (Radio Shack). |
| Performance | Highly payload dependent. |
| Frequencies | 420-470 MHz (430 MHz HAM) 470-729 MHz (UHF-TV: USA version) 800-999 MHz (ACT2: Action Band 2, cellular Blocked) SUB Rx: 50-54 MHz 137-174 MHz 420-470 MHz Tx: 50-54 MHz (MAIN & SUB) 144-146 MHz or 144-148 MHz (MAIN & SUB) 222-225 MHz ((MAIN, USA version) 430-440 MHz or 430-450 MHz (MAIN & SUB) |
| | 137-174 MHz (144 MHz HAM) 420-470 MHz (430 MHz HAM) 137-174 MHz 420-470 MHz 144-146 MHz or 144-148 MHz (MAIN & SUB) 430-440 MHz or 430-450 MHz (MAIN & SUB) |
| Operating Temperature | -20 °C to +60 °C (-4 °F to +140 °F). A -1.1 °C temperature was measured, with the balloon flying at 5500'. A shielded version against adverse weather conditions will be used for Test 2. |
| RF Power | 5.0 W (@7.4 V & 13.8 V EXT DC IN) 0.3W (@7.4 V & 13.8 V EXT DC IN, 222 MHz) |
| Max Payload | Platform dependent. 1) For a balloon configuration the max payload will be 10 pounds (with a 50 Watt radio and the ground plane antenna). Current balloon payload was less than 2 pounds with a 5 watt repeater. 2) for a UAV configuration, two options are available: i) A 5 Watt repeater with max weight of 2 pounds ii) A 200 mW repeater with max weight <u>less than 200 gm</u> (Test 3 objective). |
| Operational Environmental Limitations | For the Balloon configuration the limiting factor is only the Balloon wind speed limits. Also during high wind speeds the max alt of the tethered balloon is decreased, since the connecting cable can be tilted (not completely vertical). |

Table 2. Airborne repeater specifications.

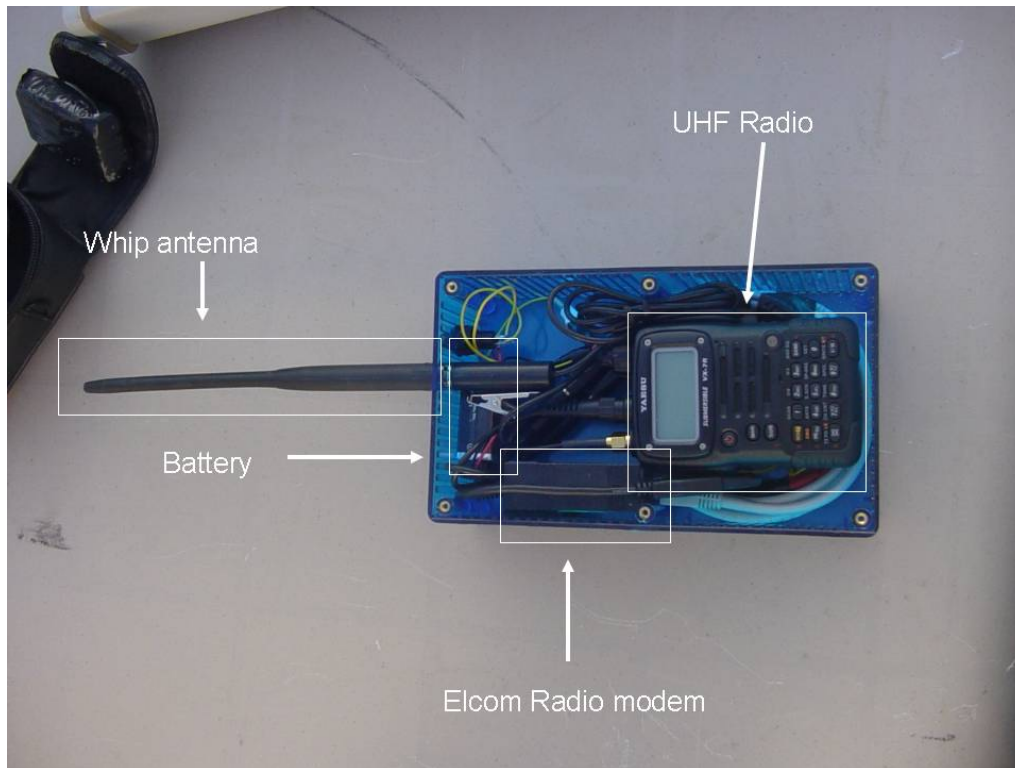


Figure 26. YAESU VX-7R/ ELCOM airborne repeater.

To create a ground plane for the airborne repeater, an antenna was constructed at the NPS microwave lab. The antenna served as a payload holder as well, and two wind socks were used to stabilize the payload.



Figure 27. Payload consisting of ground plane antenna and repeater.

- Ground station: A 5-watt YAESU VX-7R handheld radio, connected to an ELCOMs micro uTNT™ radio modem, in terminal mode.

DELL Precision Laptop / 2 GHz RAM



Figure 28. Ground station.

- Trackers:

Configuration A: A 5-watt YAESU VX-7R handheld radio connected to an ELCOMs micro uTNT™ radio modem, in Tracker mode, and a Foretrex 201 GPS receiver

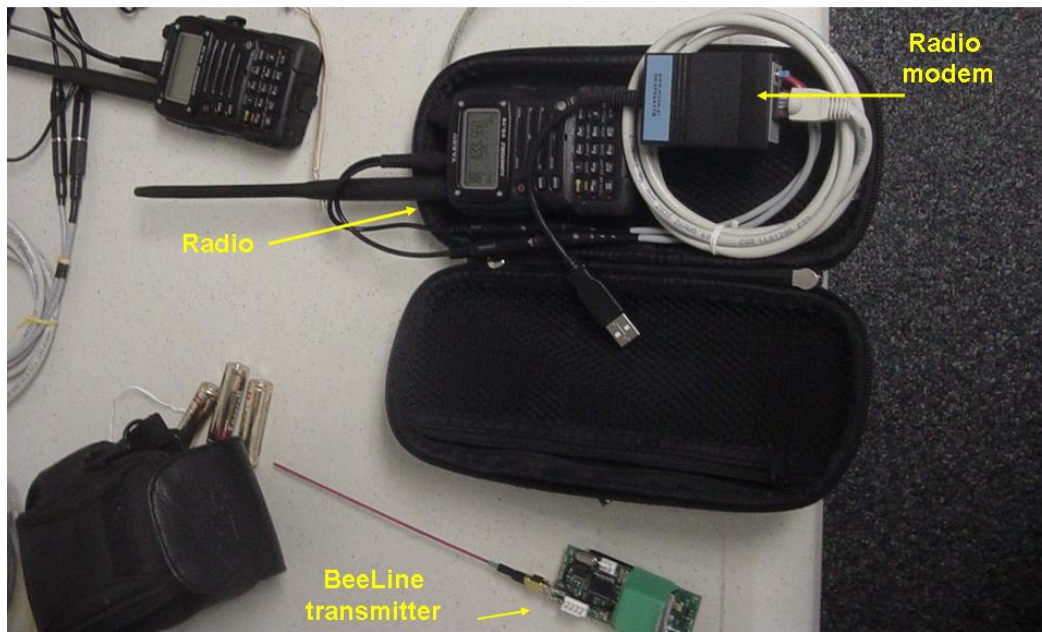


Figure 29. Tracker inside soft case, and BeeLine transmitter.

Configuration B: A 5-watt KENWOOD TH-7D handheld radio connected to a Foretrex 201 GPS receiver.

| | |
|--|--|
| Dimensions W x H x D | 54.0 x 119.5 x 35.5 mm |
| Weight | Approx 500 gm (with GARMIN Foretrex 201 GPS) |
| Crew | Manual Operator, Autonomous Operator, Sensor Operator |
| Max Speed | No limit |
| Max Range | ~5mi as limited by LOS |
| Endurance | 3 hours per battery pack. (with PB-39 Battery) 5 hours per battery pack. (with PB-39h 9.6 volt 1450mAh battery) It can also powered through the cigarette lighter adaptor for continuous operation (for example vehicle tracking) |
| Power | 13.8 V External power supply Battery terminals: 6 V |
| Performance | Highly payload dependent. Replacing the unity gain antenna with the more efficient (3.2 dBi) diamond antenna, the tracker was traced for 63 Km. |
| Frequencies | VHF: 144-148 MHz UHF: 438-450 MHz |
| Operating Temperature | -20 °C to +60 °C (-4 °F to +140 °F). |
| RF Power | VHF BAND:6W (@High mode) UHF BAND:5.5W (@High mode) |
| Operational / Environmental Limitations | i) A clear view of the sky is required so the unit can acquire the necessary GPS satellites. When the GPS has not a 3D GPS fix, the transmitter doesn't beacon its position. ii) A few transmissions were lost when the unit was in close proximity to High Voltage Power Lines. |

Table 3. KENWOOD / Foretrex APRS tracker specifications.



Figure 30. Test vehicle.



Figure 31. APRS transceiver on a pole.

Configuration C: A 12dBi Red Bee GPS tracker.

| | |
|--|---|
| Dimensions | The board measures 2 7/8" x 1 1/4", the antenna is about 6.25" long. |
| Weight | Less than 100 gr. |
| Crew | Autonomous Operator |
| Max Range | Depending of the platform altitude. Test I measurements on Red Bee were limited, although a 2NM range was covered <u>without</u> the use of a repeater. |
| Endurance | A fully charged battery should allow for updates every 2 seconds for a period of 8 hours without over discharging the battery. |
| Power | a single cell lithium polymer battery is used.. <i>Maximum input voltage without a heat sink is limited to 9V.</i> |
| Performance | Highly payload dependent. TBD on Test II metrics 420-450 MHz Adjustable between -10 dBm and 12 dBm |
| Frequencies | |
| RF Power | |
| Data Formats | The packets transmitted from the BeeLine GPS come in one of two formats: APRS and TEXT. The Text version, if enabled, transmits the latitude and longitude with 4 decimal digits of accuracy. The APRS version only transmits 2 digits of accuracy due to the format of the APRS data packet. Altitude for both packet formats is transmitted in meters above sea level. |
| Operational Environmental Limitations | |

Table 4. BeeLine APRS tracker specifications.

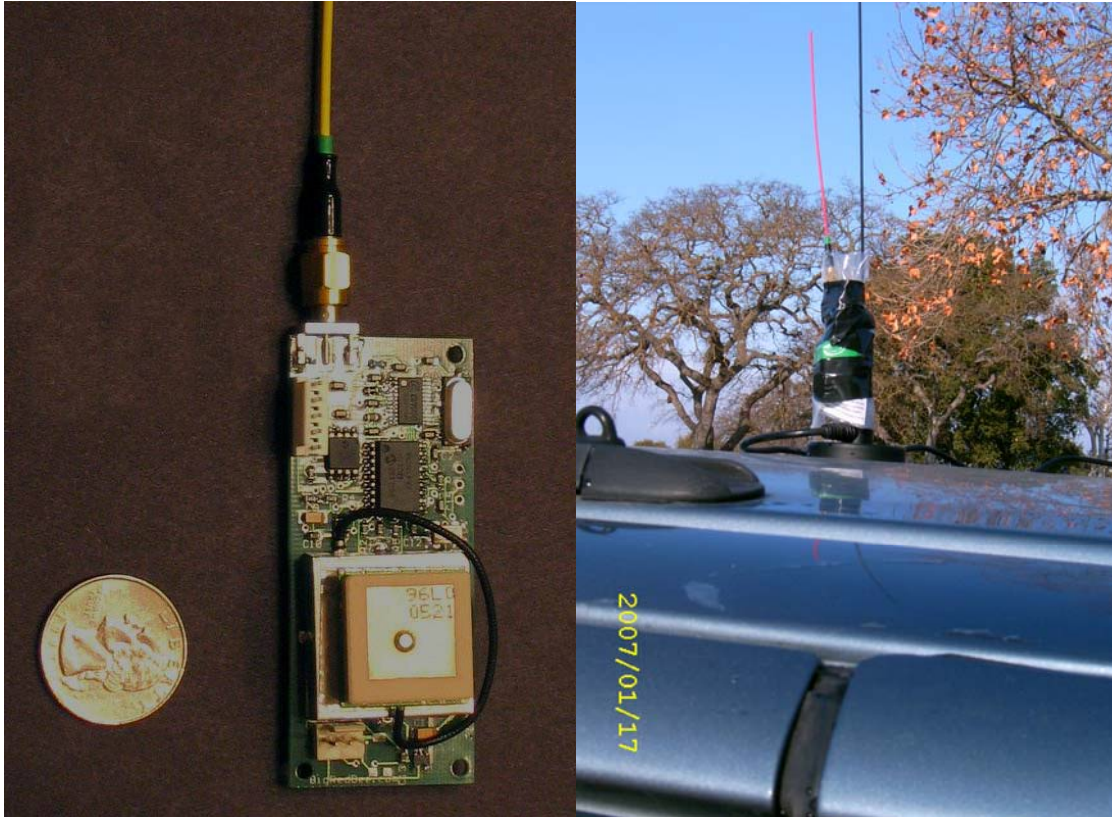


Figure 32. Beeline transmitter on a van (From [8]).

Location: Operations were conducted at McMillan Field in Camp Roberts and along a 63-km portion of Highway 101, north of Camp Roberts. The McMillan Field grid coordinates are 020548, located at coordinates $35^{\circ} 43' \text{ N}$ and $120^{\circ} 46'$; the elevation is 920' MSL; the runway is a paved surface, 65-feet wide, 3500-feet long, with 300-feet overruns at each end.

A. KENWOOD TH-7D

1. Beyond Line of Sight Measurements

The purpose of the first experiment was to create a point-to-point link with a moving asset (a vehicle) and to track it in a broad area. The vehicle was tasked to follow a path in which both a LOS and beyond-LOS connectivity could be established. Two patterns were run. The first pattern was executed without using a repeater (the tethered

balloon); the second pattern was executed using a repeater. The B configuration of the tracker was used (a KENWOOD TH-7D with a FORTREX 201 GPS unit). For both patterns the receiving unit (a YAESU VX-7R handheld radio connected to an ELCOM micro uTNT™ radio modem) was inside a one-story building, and a unity gain antenna was used.

During the first FTX there were no external antennas for the ground station, which was a limiting factor for our metrics, especially since there was also no repeater used.

Figure 33 shows the track that the vehicle was tasked to drive. It includes points where the vehicle could retain both a LOS (blue line) and a non-LOS (red line) with the receiving station.

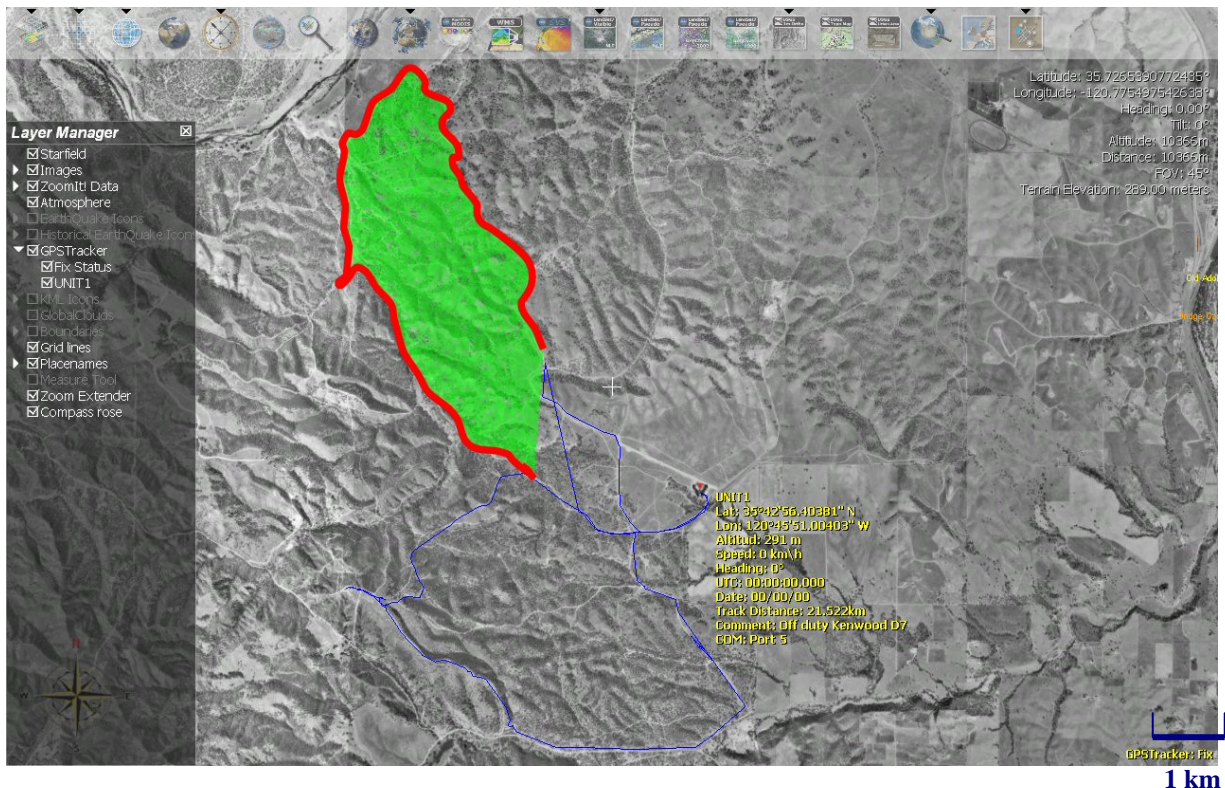


Figure 33. LOS covered path (blue line) vs. beyond-LOS uncovered path (red line).

Results:

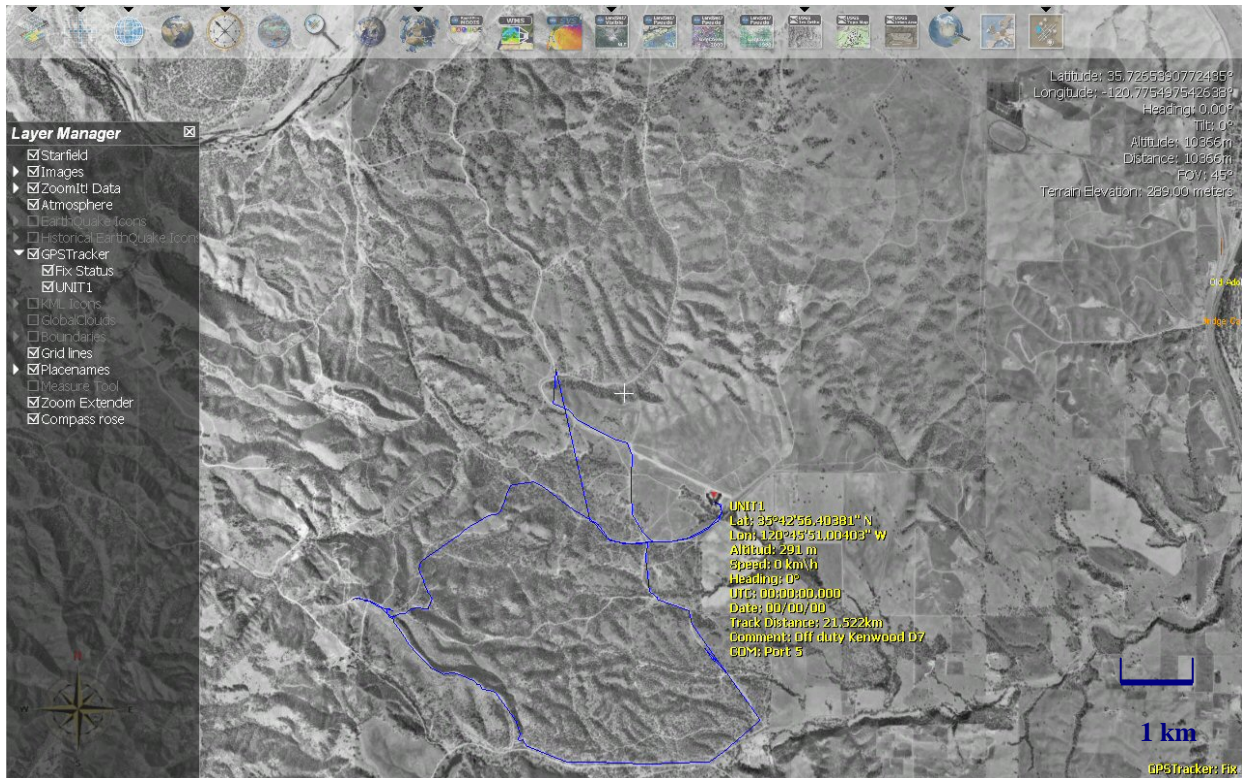


Figure 34. Covered path without the use of the repeater.

The areas behind the mountains couldn't be tracked because:

- the receiving unit, including an antenna, was inside a building, thus reducing the signal strength available to the receiver.
- the ground obstacles (mountains) were so high that the RF waves were completely obstructed.
- UHF frequencies were used, which have a shorter wavelength (430 MHz) than VHF frequencies.

Below is a sample of the received APRS positional data from the track during this session. The actual data collected from the experiment is in Appendix A: Data collection/KENWOOD TH-7D/Beyond LOS.

```
UNIT1>SUTRYS,WIDE2-2:0IrIJ_K\>"7!;
```

```

UNIT1>SUTRYQ,WIDE2-2:`0Imlq0K\>"6v}
UNIT1>SUTRXW,WIDE2-2:`0Ikm!.K\>"6r}
UNIT1>SUTRXQ,WIDE2-2:`0InnJ/K\>"6r}
UNIT1>SUTRWW,WIDE2-2:`0IvnrFK\>"6r}
UNIT1>SUTRWP,WIDE2-2:`0J"o@FK\>"6s}
UNIT1>SUTRVX,WIDE2-2:`0Jlo,aK\>"6t}
UNIT1>SUTRVX,WIDE2-2:`0J;n|bK\>"6z}
UNIT1>SUTRWT,WIDE2-2:`0JCnA<K\>"7"}
UNIT1>SUTRXU,WIDE2-2:`0JKo7CK\>"7#{

```

It is obvious that a repeating path wasn't used, only a WIDE2-2 indication without reduction on the second digit. Also, during this version of GPSTracker we did not reconstruct a timestamp so a raw mic-E APRS format was used. This is a very efficient format due to the short length of the transmitted sentence (smaller amount of data), but it doesn't use a timestamp. In subsequent versions of GPSTracker, we compiled code so we could append a timestamp on the receiving end to every sentence that didn't have one like the mic-E format.

The next day we used an airborne repeater (A 5-watt YAESU VX-7R handheld radio connected to an ELCOM micro uTNT™ radio modem in digipeating mode), so LOS could be established and the signal could get back to the Command and Control center. This time, the fact that the receiving station was inside a building was not a limiting factor, because the repeating unit was flying right above the ground station at an elevation of 2000 feet above ground level (AGL), as shown in Figure 35.



Figure 35. Tethered balloon location.

The plot in Figure 36 shows the covered path with the use of the repeater. This time, the vehicle followed only the path that was not covered during the previous experiment.

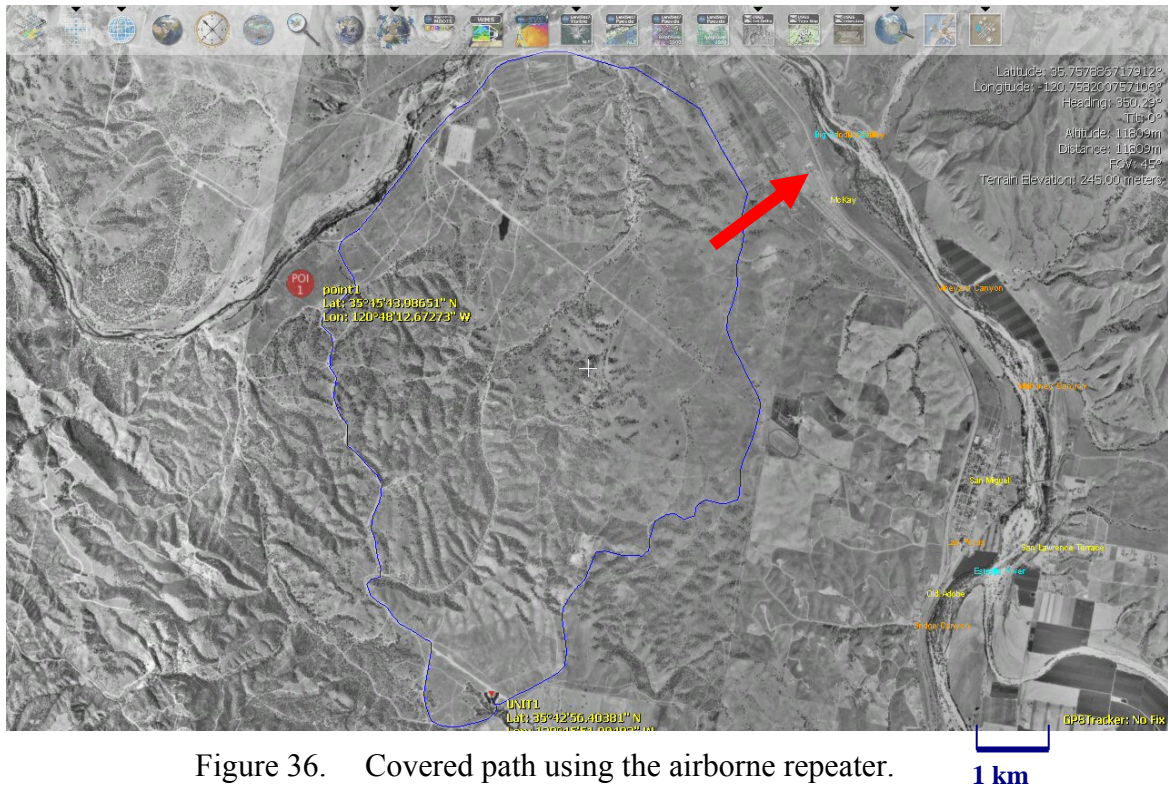


Figure 36. Covered path using the airborne repeater.

1 km

Results:

1. Almost the whole area was covered during the experiment.
2. This was because the repeater was able to cover the beyond-visual-range points (BVR).
3. A small area was not covered (red arrow).
4. This was because there were high-voltage power lines in the vicinity that completely covered the UHF transmissions (Figure 37).

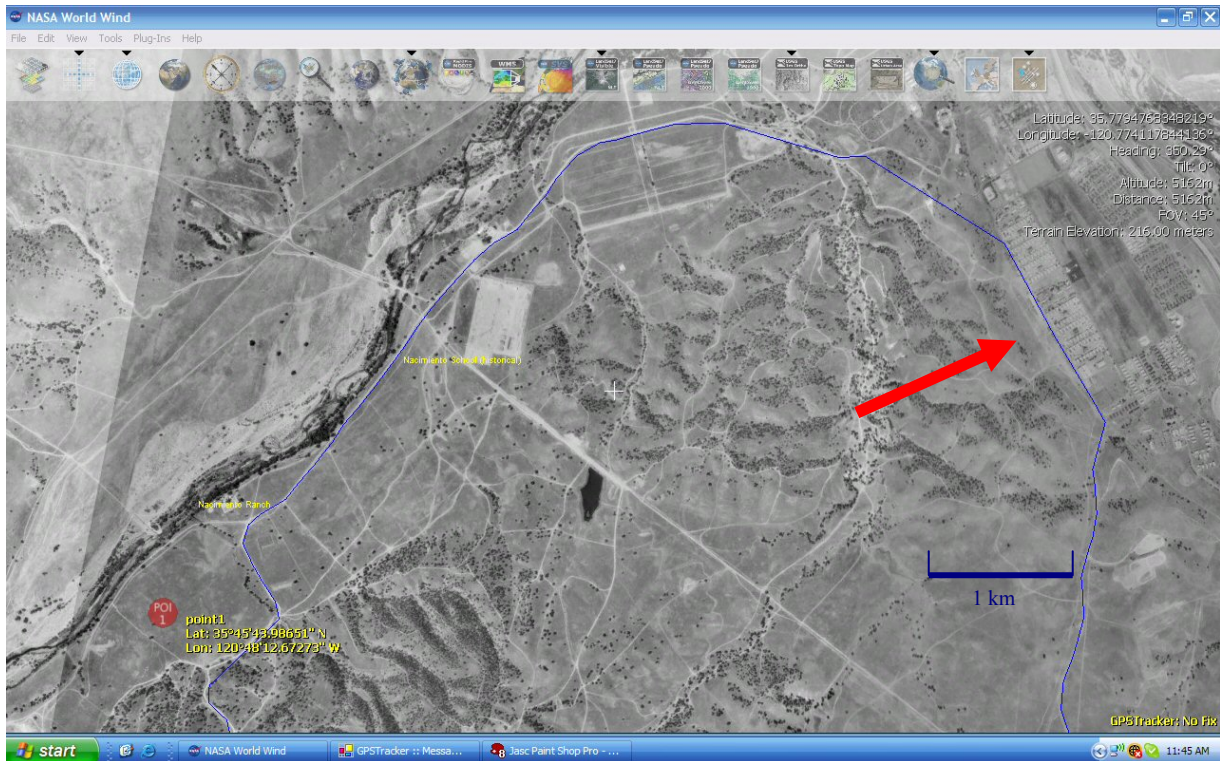


Figure 37. High-voltage power lines block the transmissions.

Below we see a sample from the received APRS positional data from the track during that session. The actual data collected from this experiment can be found in Appendix A: Data collection/KENWOOD TH-7D/ LOS.

```
UNIT1>SUTRYT,WIDE2-2:`0Iql,{K\>"6\}
UNIT1>SUTRYT,WIDE2-1:`0Iql,{K\>"6\}
UNIT1>SUTRYT,WIDE2-2:`0Irl6&K\>"6\}
UNIT1>SUTRYT,WIDE2-1:`0Irl6&K\>"6\}
UNIT1>SUTRYS,WIDE2-2:`0Iqlg_K\>"6\}
UNIT1>SUTRYS,WIDE2-1:`0Iqlg_K\>"6\}
UNIT1>SUTRYQ,WIDE2-2:`0Inlg2K\>"6\}
UNIT1>SUTRYQ,WIDE2-1:`0Inlg2K\>"6\}
UNIT1>SUTRXX,WIDE2-2:`0Iklq/K\>"6\}
UNIT1>SUTRXX,WIDE2-1:`0Iklq/K\>"6\}
```

In the above sentences it is obvious that a repeater was used, because the digipeating number is reduced sequentially with every transmission, from WIDE2-2 to WIDE2-1.

2. Maximum Range Measurements

The purpose of the second experiment was to measure the maximum distance that a tracker can be detected when unobstructed by terrain features. We installed the Configuration B of the trackers (a 5-watt KENWOOD TH-7D handheld radio connected to a Foretrex 201 GPS receiver) on a vehicle; and the vehicle was tasked to drive along Hiway 101, from Camp Roberts all the way northbound (Figure 13). The receiving unit (a YAESU VX-7R handheld radio connected to an ELCOM micro uTNT™ radio modem) was inside a one-story building and a unity gain antenna was used. Again, an airborne repeater was launched (a 5-watt YAESU VX-7R handheld radio connected to an ELCOM micro uTNT™ radio modem in digipeating mode), so LOS could be established and get the entire transmitted data back to the Command and Control center.

The transmission rate was set at once every 12 seconds (the minimum transmission rate permitted by the KENWOOD APRS radio). Communication with the vehicle driver was via cell phones.

Results: Figure 38 shows the overall plot of the vehicle's track on California Highway 101.

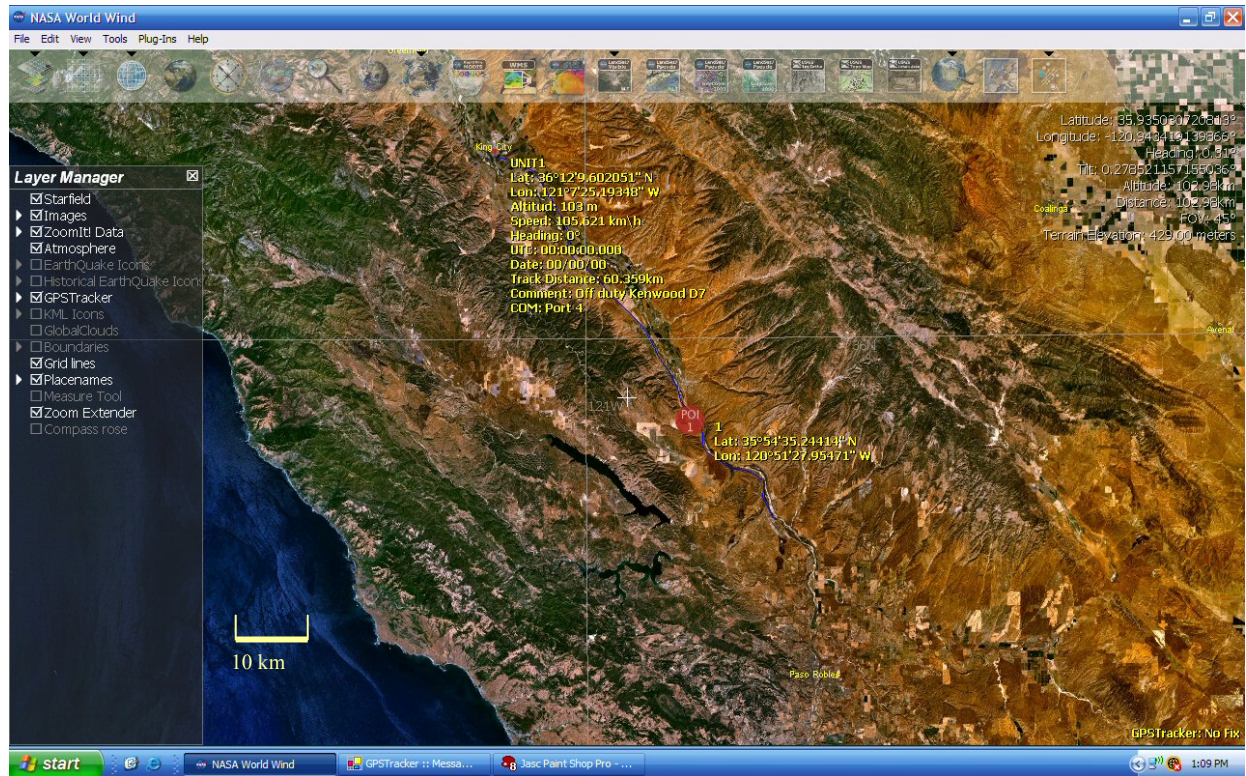


Figure 38. Highway 101, maximum range measurements.

The total distance covered was 63.2 km from point-to-point, shown in Figure 39.



Figure 39. 63.2 km of continuous tracking.

At this point the direct link with the receiving airborne repeater could not be retained because the mountains in the area prevented the maintenance of the line of sight (Figure 40). Furthermore, the airborne repeater was stabilized at an altitude of 2000 feet AGL, because high wind conditions prevented deployment to a higher altitude.

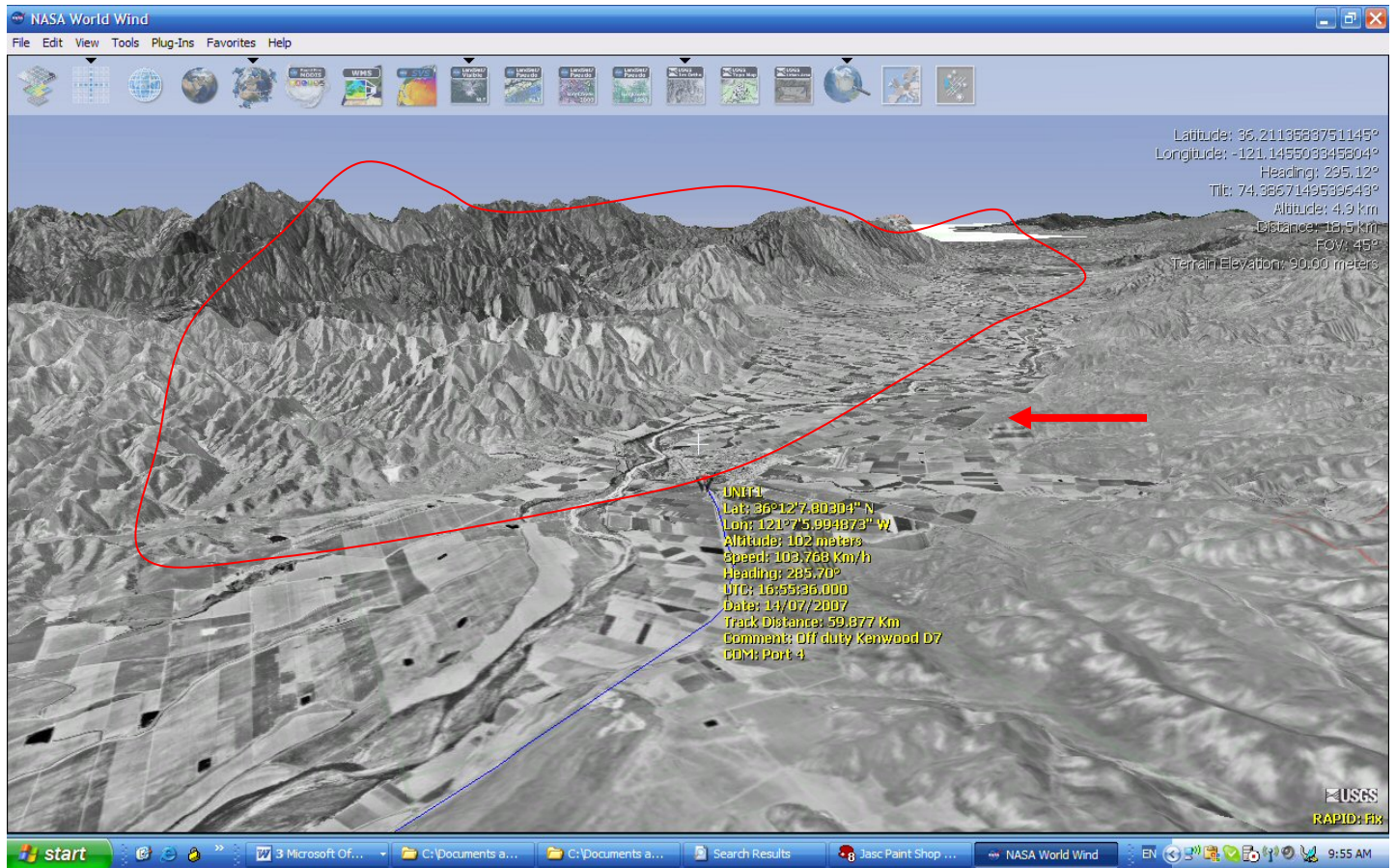


Figure 40. High-altitude mountains prevented retention of the line-of-sight.

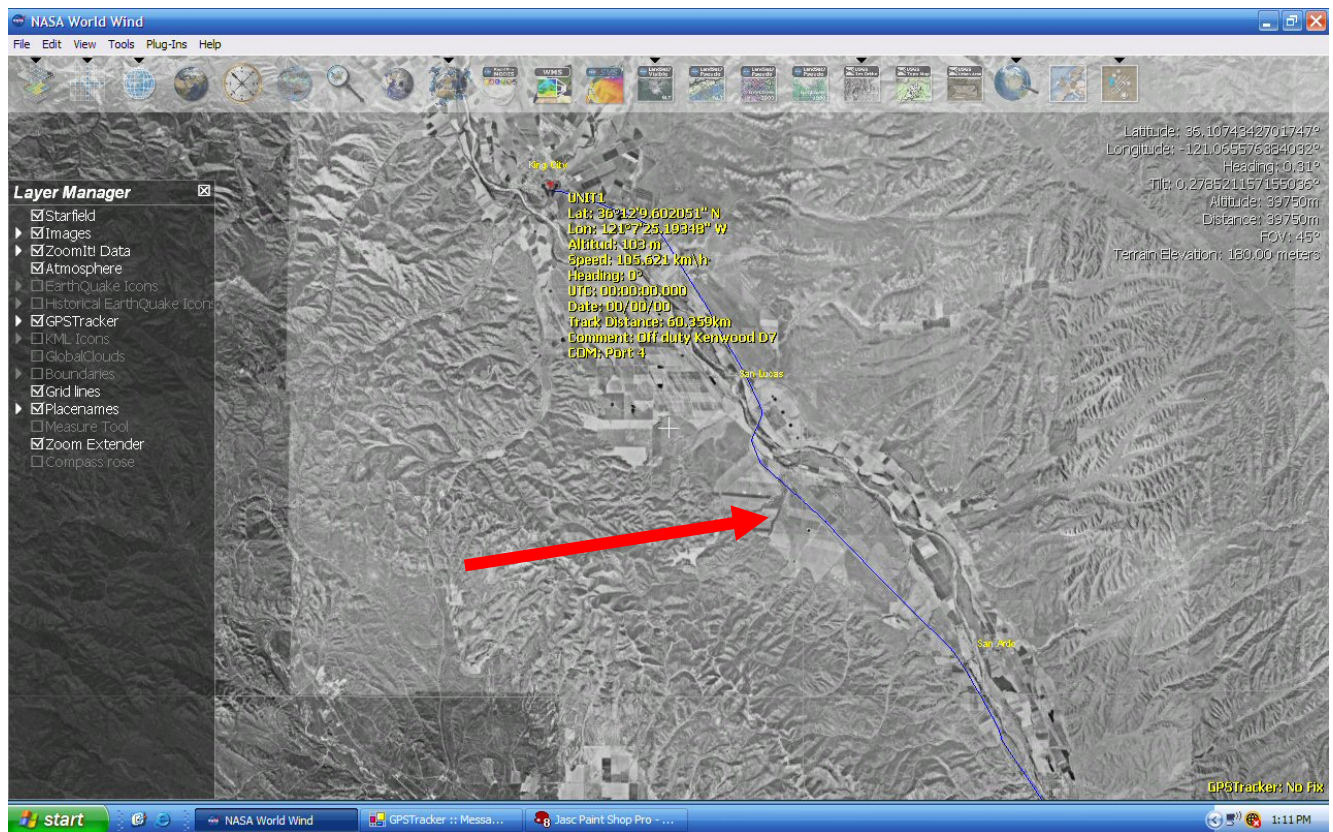


Figure 41. High voltage power lines along Hwy 101.

All of the transmissions were received by the ground station except for a very narrow section where once again interference from high-voltage power lines along the highway masked the transmissions (Figure 41):

Below is a sample of the received APRS positional data from the track during that session. The actual data collected from this experiment is in Appendix A: Data collection/KENWOOD TH-7D/Max Range.

```
UNIT1>SUTWYW,WIDE2-1:0HRI#_K\>"3r}
UNIT1>SUTWYW,WIDE2-1:0HRI#_K\>"6#}
UNIT1>SUTWYW,WIDE2-1:0HRI#_K\>"6{
UNIT1>SUTWYW,WIDE2-1:0HRI#_K\>"6.}
UNIT1>SUTWYW,WIDE2-1:0HRI#_K\>"61}
UNIT1>SUTWYX,WIDE2-1:0HRI#_K\>"64}
UNIT1>SUTWYX,WIDE2-1:0HRI#_K\>"67}
UNIT1>SUTWYX,WIDE2-1:0HRI#_K\>"6.}
UNIT1>SUTWYX,WIDE2-1:0HRI#_K\>"69}
```

In the transmission path of the above received sentences, we see none of the data received directly by the ground station, but all of the data received through the airborne repeater (only WIDE2-1 indications; no WIDE2-2 indications).

Below is a comparison of the range achieved during this experiment with the theoretical values and our conclusions concerning the collective experiment metrics. The budget for the established link can be determined by the following formula:

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} - L_{RX} \quad [9]$$

where:

P_{RX} = received power (dBm)

P_{TX} = transmitter output power (dBm)

G_{TX} = transmitter antenna gain (dBi)

L_{TX} = transmitter losses (coax, connectors) (dB)

L_{FS} = free space loss or path loss (dB)

L_M = miscellaneous losses (polarization mismatch, other losses) (dB)

G_{RX} = receiver antenna gain (dBi)

L_{RX} = receiver losses (coax, connectors) (dB)

For this experiment, the corresponding values were:

P_{TX} = transmitter output power = 5 Watts (or 37 dBm)

G_{TX} = transmitter antenna gain = 3 dBi

L_{TX} = transmitter losses = 3.2 dB ⁱ

L_{FS} = free space loss or path loss = 121 dB ⁱⁱ

L_M = miscellaneous losses = 3dB ⁱⁱⁱ

G_{RX} = receiver antenna gain = 0 dBi (whip antenna)

L_{RX} = receiver losses = 3 dB ^{iv}

Replacing all the above values to the Link Budget formula we get:

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} - L_{RX} \Leftrightarrow$$

$$P_{RX} = 37 + 3 - 3.2 - 121 - 3 + 0 - 3 = -90 \text{ dB}$$

Our YAESU VX-7R receiver sensitivity (P_{RS}) was 0.18 μ V for 12 dB SINAD (Signal plus Noise plus Distortion to Noise plus Distortion ratio) at frequency ranges of 400-470 MHz N-FM.

Converting this value to dB μ V we get:

$$P_{RS} = 20 \log_{10}(0.18) = -15 \text{ dB}\mu\text{V}.$$

Subsequently we convert dB μ V to dBm with 50 Ω impedance by subtracting 107 dB:

$$P_{RS} = -14.9 - 107 = -122 \text{ dBm}$$

This is the minimum receive level with 12 dB SINAD margin. Also thermal noise at 23 °C is -138 dBm for bandwidth of 3400 Hz at 1200 baud so -138 dBm < -122 dBm at 12 SINAD threshold for P_{RX} sensitivity. Reception is reliable when $P_{RX} > P_{RS}$. For our experiment we have:

$$P_{RX} = -90\text{dBm} > P_{RS} = -122\text{ dBm}, \text{ so reception is reliable and allows a margin of } -122\text{dBm} - (-90\text{dBm}) = 32\text{ dB}.$$

If we conservatively assume that a margin of 20 dB is the minimum value required for a reliable communications link, then the received power can be as low as $P_{RXmin} = -89\text{ dBm} - (32 - 20)\text{ dB} = -101\text{ dBm}$. So the question that arises is: What is the distance between the transmitter and the receiver that will deliver -101 dBm at the receiver site? It will be the maximum theoretical distance (using the same equipment) that the transmitter can be separated from the receiver and still be a reliable link. The Link budget equation is solved by looking for the new distance d_{max} , now using the P_{RXmin} value of -100 dBm.

$$P_{RXmin} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} - L_{RX} \Leftrightarrow$$

$$L_{FS} = P_{TX} + G_{TX} - L_{TX} - P_{RXmin} - L_M + G_{RX} - L_{RX} \Leftrightarrow$$

$$20 \log_{10}(d_{max}) + 20 \log_{10}(f) - 147.55 = P_{TX} + G_{TX} - L_{TX} - P_{RXmin} - L_M + G_{RX} - L_{RX} \Leftrightarrow$$

$$20 \log_{10}(d_{max}) = P_{TX} + G_{TX} - L_{TX} - P_{RXmin} - L_M + G_{RX} - L_{RX} - 20 \log_{10}(f) + 147.55 \Leftrightarrow$$

$$20 \log_{10}(d_{max}) = 37 + 3 - 3.2 + 101 - 3 + 0 - 3 - 172.6 + 147.5 \Leftrightarrow$$

$$\log_{10}(d_{max}) = 5.3 \Leftrightarrow d_{max} = 200\text{ km}$$

We concluded that the range achieved with the specific equipment set-up (63.2 km) was the 32% expected from the theoretical values (200 km). The main reason for the difference is that we stopped the experiment when the APRS-equipped vehicle that we were tracking reached a mountainous area, shown in Figure 40, since the line-of-sight could not be achieved with the receiving station. Also, the airborne node induced oscillations that were several times in excess of 70 degrees from the vertical position, resulting in an increased polarization mismatch. One solution to this issue is to place the airborne antenna on a mechanical gyroscope to keep it as close to vertical as possible, thus minimizing the wind effects.

ⁱ We used 12 feet of RG-58 U/A coaxial cable with losses 10.4 dB per 100 feet that equals 1.2 dB and 4 SMA connectors with 0.5 dB loss per connector equals 2 dB so we have total transmitter losses of 3.2 dB).

ⁱⁱ The equation for free-space loss is:

$$L_{FS} = (4\pi d \div \lambda)^2 = (4\pi d f \div c)^2$$

where:

λ is the signal wavelength (in meters),

f is the signal frequency (in hertz),

d is the distance from the transmitter to the receiver (in meters),

c is the speed of light in a vacuum, 3×10^8 meters per second.

This equation is only accurate in the far field; it does not apply close to the transmitter.

Expressing free space loss in dB we get:

$$L_{FS} \text{ (dB)} = 10 \log_{10} \left[(4\pi d f \div c)^2 \right] = 20 \log_{10} (4\pi d f \div c) =$$

$$20 \log_{10}(d) + 20 \log_{10}(f) + 20 \log_{10}(4\pi \div c) =$$

$$20 \log_{10}(d) + 20 \log_{10}(f) - 147.55$$

In this experiment the distance achieved was 68.2 Km (or 68200 meters) and the frequency was 430 MHz (or 430×10^6 Hz). Replacing these values to the above formula we get:

$$L_{FS} \text{ (dB)} = 20 \log_{10}(d) + 20 \log_{10}(f) - 147.55 =$$

$$20 \log_{10}(68200) + 20 \log_{10}(430 \times 10^6) - 147.55 =$$

$$96 + 172.67 - 147.55 \approx 121 \text{ dB}$$

ⁱⁱⁱ When the transmitting and receiving antennas are both linearly polarized and not aligned properly, a polarization mismatch loss will be induced that can be determined by

$$\text{Polarization Mismatch Loss (dB)} = 20 \log (\cos \theta) [10]$$

where θ is the angle between the two antennas. For a 15° misalignment angle the loss is 0.3 dB; for 30° it is 1.25 dB; for 45° , 3 dB and for 90° , we have a theoretical infinite loss. In our experiment, though we used wind socks to stabilize the airborne repeater we noticed that when the balloon was raised at an altitude above 1000 feet Mean Sea Level (MSL), high-speed winds at a range of 10 knots to 15 knots per hour resulted in payload oscillations at an average magnitude of $\approx 45^\circ$. According to the Polarization Mismatch Loss formula, this results on a polarization mismatch of 3 dB.

^{iv} I used 4 feet of RG-174 thin coaxial cable with losses of 25 dB per 100 feet that equals 1dB and 4 SMA connectors with a 0.5 dB loss per connector that equals 2 dB. So we have total transmitter losses of 3 dB.

B. BEELINE GPS

The objective here was to measure the maximum distance that transmissions from the BeeLine transmitter could be received from the ground station. A balloon repeater was launched to 1300 feet AGL (right above the receiving station), so a line-of-sight could be achieved. The transmitter was placed on the roof of a vehicle and the vehicle was tasked to drive along Hwy 101.

1. Maximum Range Measurements

The recorded file from this session shows that the maximum distance measured was 19 kilometers. However, due to the low altitude of the balloon (1300 feet AGL) and the low power settings on the transmitter (20 mW), there were several blind spots where the airborne repeater could not receive the transmissions, especially when the vehicle was behind terrain obstacles.

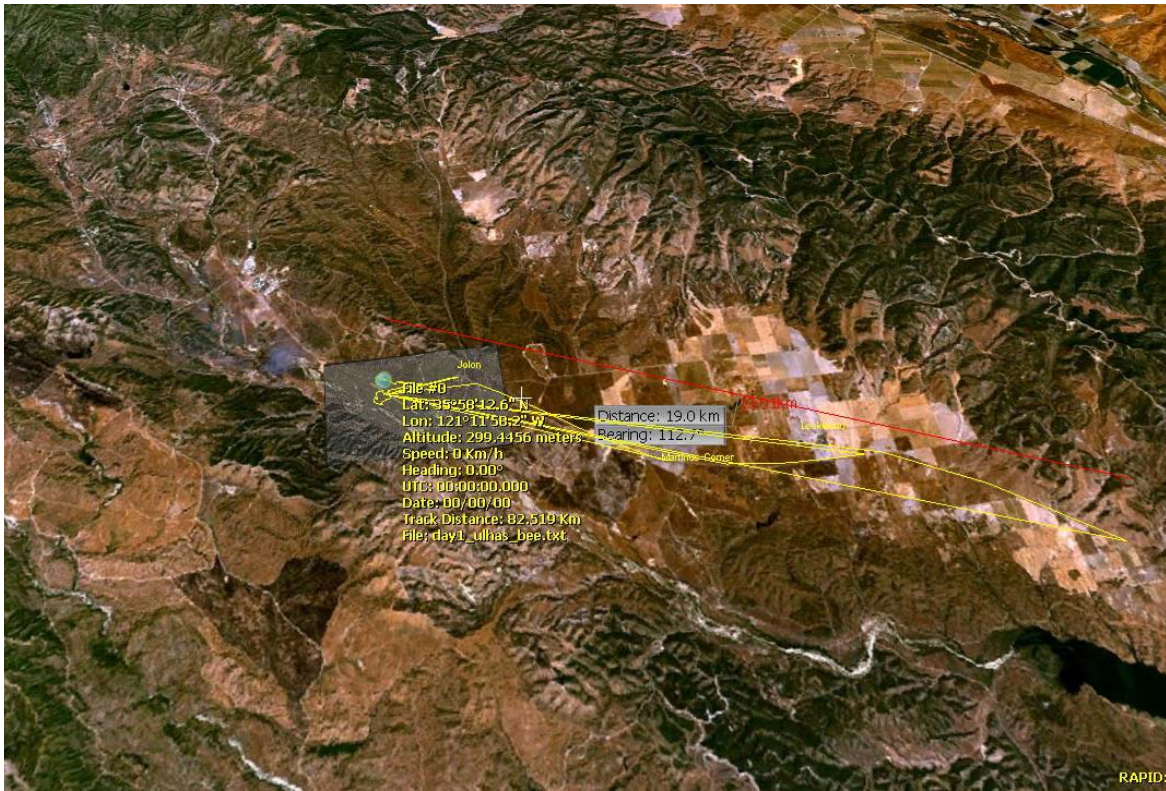


Figure 42. BeeLine GPS range determination.

The data collected from this session was transformed to raw NMEA GPGGA sentences. Below is a sample of the received sentences from the track during that session. The actual data collected from this experiment is in Appendix A: Data collection /BeeLine.

```
$GPGGA,000000,3558.150,N,12111.820,W,1,12,0.5,0000.0,M,0,M,,,*,4F
$GPGGA,000000,3558.140,N,12111.780,W,1,12,0.5,0000.0,M,0,M,,,*,4B
$GPGGA,000000,3558.140,N,12111.780,W,1,12,0.5,0000.0,M,0,M,,,*,4B
$GPGGA,000000,3558.170,N,12111.770,W,1,12,0.5,0000.0,M,0,M,,,*,47
$GPGGA,000000,3558.170,N,12111.760,W,1,12,0.5,0000.0,M,0,M,,,*,46
$GPGGA,000000,3558.170,N,12111.760,W,1,12,0.5,0000.0,M,0,M,,,*,46
$GPGGA,000000,3558.160,N,12111.710,W,1,12,0.5,0000.0,M,0,M,,,*,40
$GPGGA,000000,3558.120,N,12111.570,W,1,12,0.5,0000.0,M,0,M,,,*,40
$GPGGA,000000,3558.090,N,12111.340,W,1,12,0.5,0000.0,M,0,M,,,*,4F
$GPGGA,000000,3557.900,N,12111.920,W,1,12,0.5,0528.0,M,0,M,,,*,43
```

Below is a comparison of the range achieved during this experiment with the theoretical values and our conclusions concerning the collective experiment metrics. The budget for the established link can be determined by the following formula:

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} - L_{RX} \quad [9]$$

where:

P_{RX} = received power (dBm)

P_{TX} = transmitter output power (dBm)

G_{TX} = transmitter antenna gain (dBi)

L_{TX} = transmitter losses (coax, connectors) (dB)

L_{FS} = free space loss or path loss (dB)

L_M = miscellaneous losses (polarization mismatch, other losses) (dB) ⁱⁱⁱ

G_{RX} = receiver antenna gain (dBi)

L_{RX} = receiver losses (coax, connectors) (dB)

For this experiment, the corresponding values were:

P_{TX} = transmitter output power = 20 mW (or 13 dBm)

G_{TX} = transmitter antenna gain = 2 dBi

L_{TX} = transmitter losses = 1 dB ⁱ

L_{FS} = free space loss or path loss = 110 dB ⁱⁱ

L_M = miscellaneous losses = 3dB ⁱⁱⁱ

G_{RX} = receiver antenna gain = 0 dBi (whip antenna)

L_{RX} = receiver losses = 3 dB ^{iv}

Replacing all the above values to the Link Budget formula we get:

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} - L_{RX} \Rightarrow$$

$$P_{RX} = 13 + 2 - 1 - 110 - 3 + 0 - 3 = -102 \text{ dB}$$

Our YAESU VX-7R receiver sensitivity (P_{RS}) was 0.18 μV for 12 dB SINAD (Signal-Including- Noise-And- Distortion) at frequency ranges of 400-470 MHz N-FM.

Converting this value to dB μV we get:

$$P_{RS} = 20 \log_{10}(0.18) = -15 \text{ dB}\mu\text{V}.$$

Subsequently we convert dB μV to dBm with 50 Ω impedance by subtracting 107 dB:

$$P_{RS} = -14.9 - 107 = -122 \text{ dBm}$$

Reception is reliable when $P_{RX} > P_{RS}$. For our experiment we have:

$P_{RX} = -102 \text{ dBm} > P_{RS} = -122 \text{ dBm}$, so reception is reliable and allows a margin of $-122 \text{ dBm} - (-102 \text{ dBm}) = 20 \text{ dB}$. If we assume that a margin of 20 dB is the minimum value required for a reliable communications link, then we conclude that the range achieved (18 km) was the maximum range for the BeeLine transmitter.

ⁱ We used 2 SMA connectors with a 0.5 dB loss per connector that equals 1 dB, for attaching the antenna to the transmitter

ⁱⁱ The equation for free-space loss is:

$$L_{FS} = (4\pi d \div \lambda)^2 = (4\pi df \div c)^2$$

where:

λ is the signal wavelength (in meters),

f is the signal frequency (in hertz),

d is the distance from the transmitter to the receiver (in meters),

c is the speed of light in a vacuum, 3×10^8 meters per second.

This equation is only accurate in the far field; it does not apply close to the transmitter.

Expressing free space loss in dB we get:

$$L_{FS} \text{ (dB)} = 10 \log_{10} \left[(4\pi df \div c)^2 \right] = 20 \log_{10} (4\pi df \div c) =$$

$$20 \log_{10}(d) + 20 \log_{10}(f) + 20 \log_{10}(4\pi \div c) =$$

$$20 \log_{10}(d) + 20 \log_{10}(f) - 147.55$$

In this experiment the distance achieved was 18 Km (or 18000 meters) and the frequency was 430 MHz (or 430×10^6 Hz). Replacing these values to the above formula we get:

$$L_{FS} \text{ (dB)} = 20 \log_{10}(d) + 20 \log_{10}(f) - 147.55 =$$

$$20 \log_{10}(18000) + 20 \log_{10}(430 \times 10^6) - 147.55 = 85 + 172.67 - 147.55 \approx 110 \text{ dB}$$

ⁱⁱⁱ When the transmitting and receiving antennas are both linearly polarized and not aligned properly, a polarization mismatch loss will be induced that can be determined by

$$\text{Polarization Mismatch Loss (dB)} = 20 \log (\cos \theta) \text{ [10]}$$

where θ is the angle between the two antennas. For a 15° misalignment angle the loss is 0.3 dB; for 30° it is 1.25 dB; for 45° , 3 dB and for 90° , we have a theoretical infinite loss. In our experiment, though we used wind socks to stabilize the airborne repeater we noticed that when the balloon was raised at an altitude above 1000 feet Mean Sea Level (MSL), high-speed winds at a range of 10 knots to 15 knots per hour resulted in payload oscillations at an average magnitude of $\approx 45^\circ$. According to the Polarization Mismatch Loss formula, this results on a polarization mismatch of 3 dB.

^{iv} We used 4 feet of RG-174 thin coaxial cable with losses of 25 dB per 100 feet that equals 1dB and 4 SMA connectors with a 0.5 dB loss per connector that equals 2 dB. So we have total transmitter losses of 3 dB.

A significant measurement performed that day is presented below.

During this test, a microwave (9 kHz-20 GHz) spectrum analyzer was used to measure the received signal strength of the bee line transmitter. As the plots in Figures 43 through 47 show, the signal power reduced with distance, and we cannot discriminate between signal and surrounding noise at a distance of 400 meters from the 20-mw transmitter. Nevertheless, as was the case in the maximum-distance performance test of this particular transmitter, we were able to receive and demodulate the positional data much farther away than 400 meters. This is primarily due to the BFSK modulation scheme that is used by this specific transmitter and the high compression of the GPS NMEA sentence that the APRS format performs. This compression allows the transmission of a small amount of data every time the transmitter is keyed, so the potential for errors is relatively low.

The spectrum analyzer used was the: MS2721AANRITSU Spectrum monitor, Radio Recon Flex Master. The noise floor was greater than -80 dBm so self noise in the measurement system masked distant far field measurements. The antenna was a 0 dBi gain omni monopole and the receiving range was set to 0-3.2 GHz. The data collected are presented below:

Measuring distance: 0 meters from the receiver

Received signal gain: -34 dBm

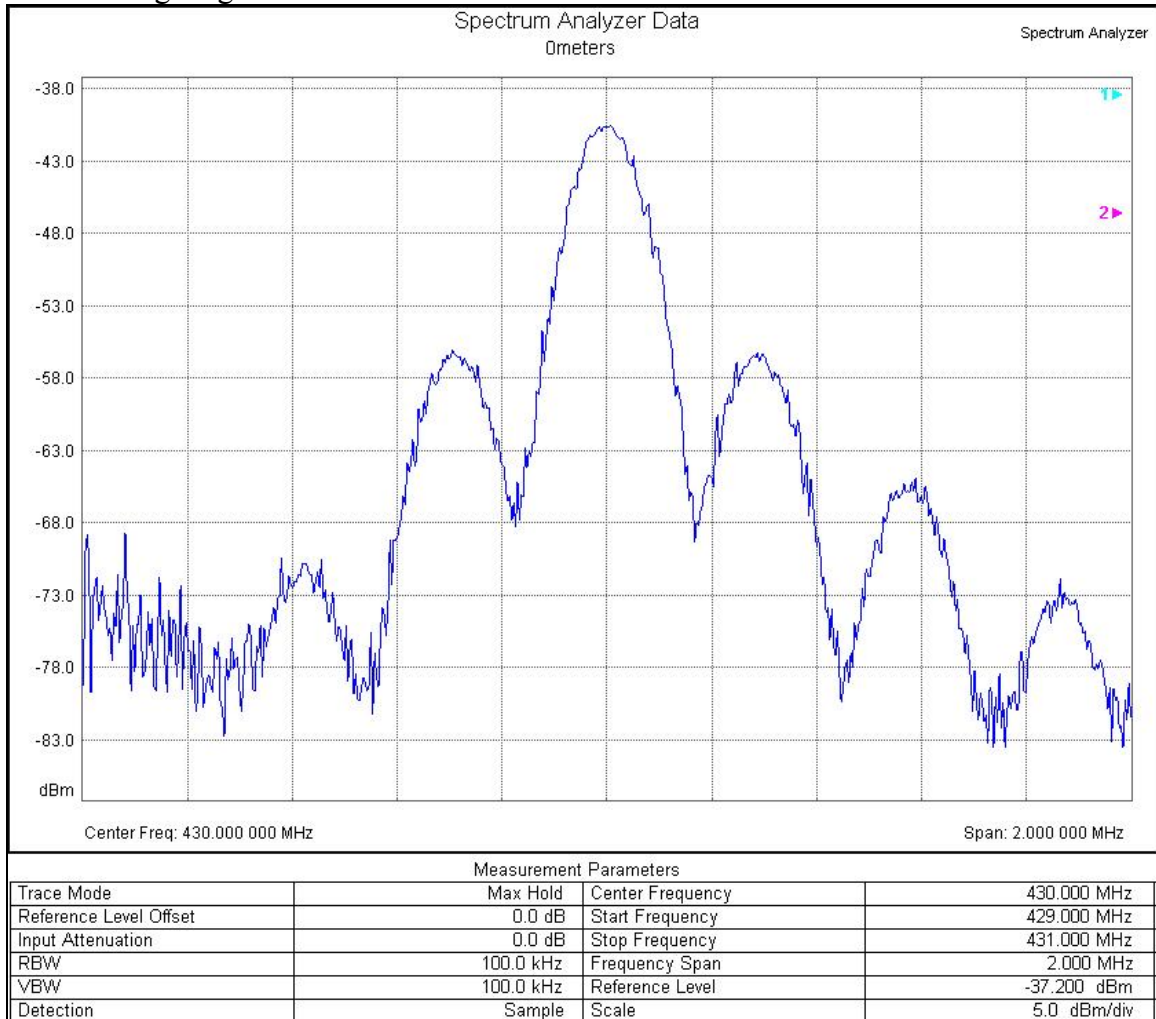


Figure 43. Spectrum analyzer at 0 meters from the transmitter.

Measuring distance: 100 meters from the receiver

Received signal gain: -54.2 dBm

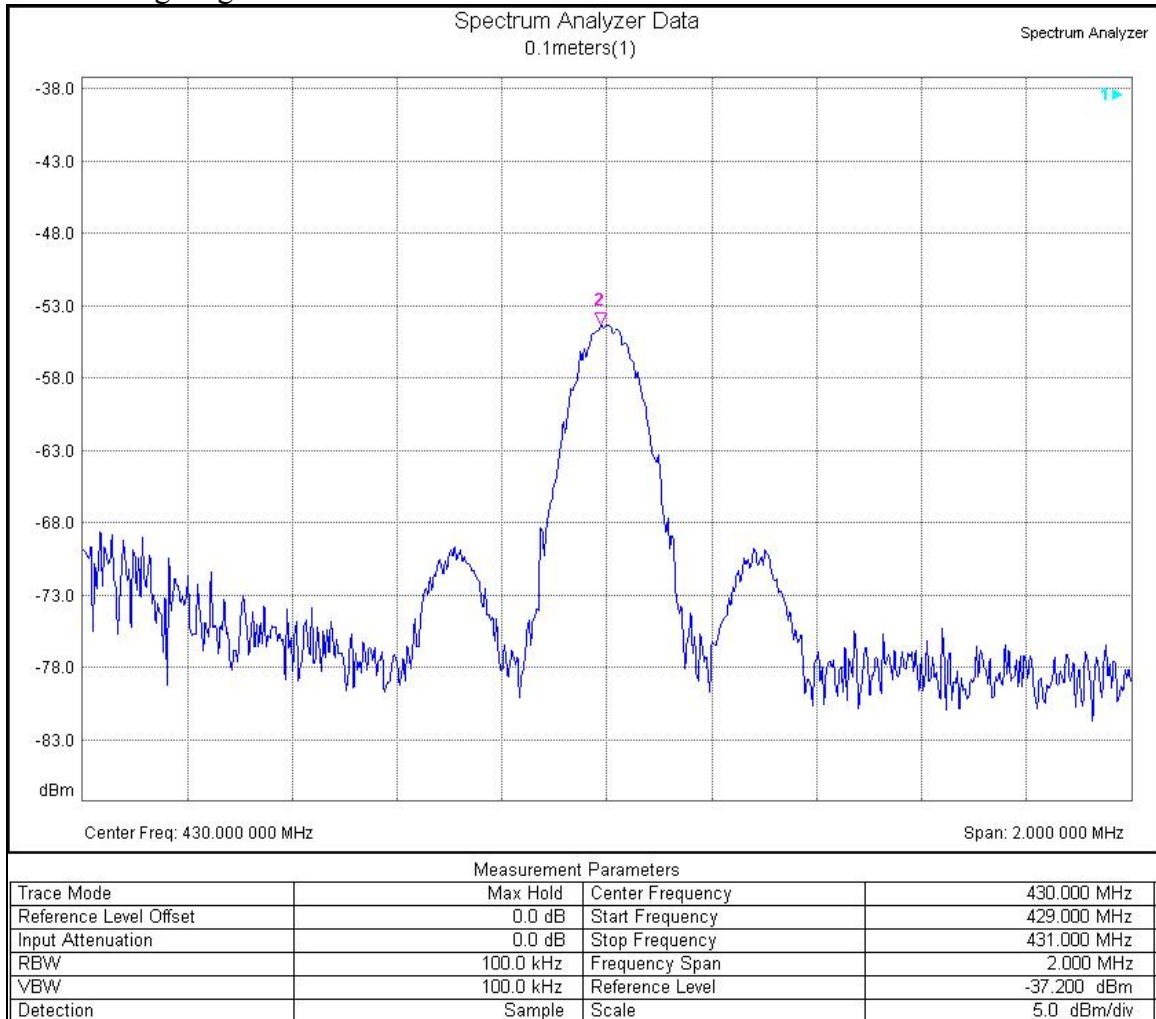


Figure 44. Spectrum analyzer at 100 meters from the transmitter.

Measuring distance: 200 meters from the receiver

Received signal gain: -68.14 dBm

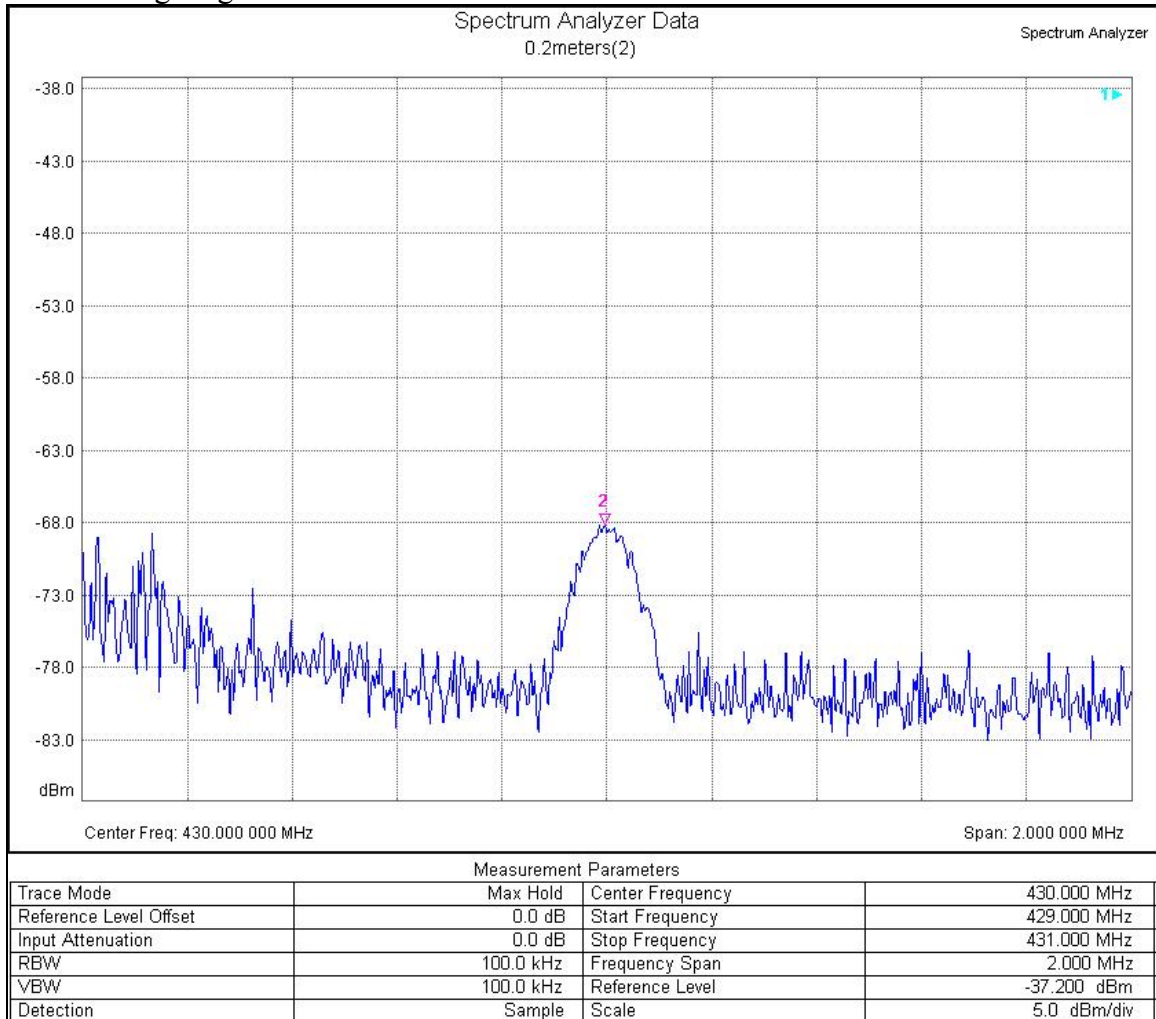


Figure 45. Spectrum analyzer at 200 meters from the transmitter.

Measuring distance: 300 meters from the receiver

Received signal gain: -73.12 dBm

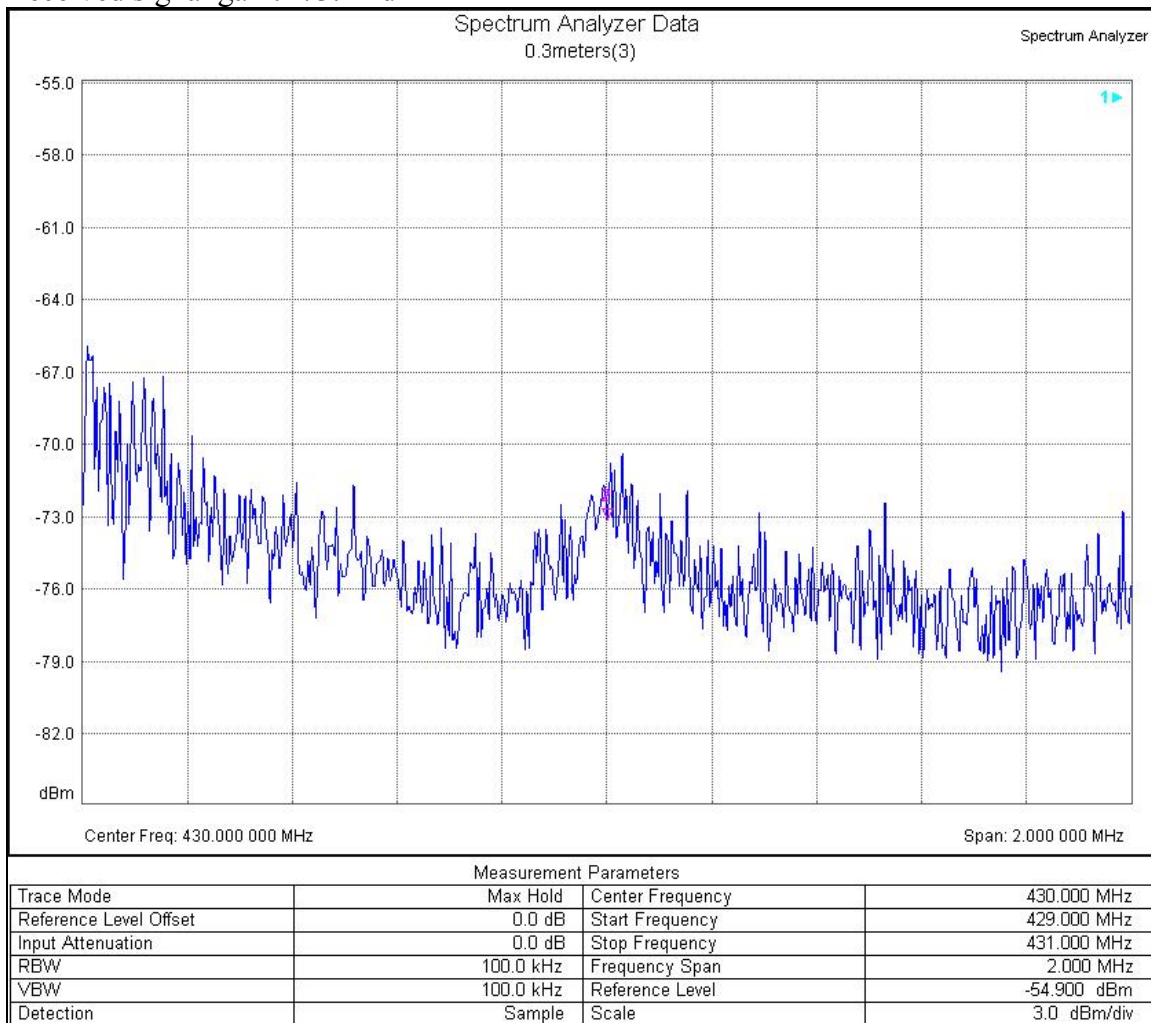


Figure 46. Spectrum analyzer at 300 meters from the transmitter.

Measuring distance: 400 meters from the receiver

Received signal gain: -75dBm (signal = noise)

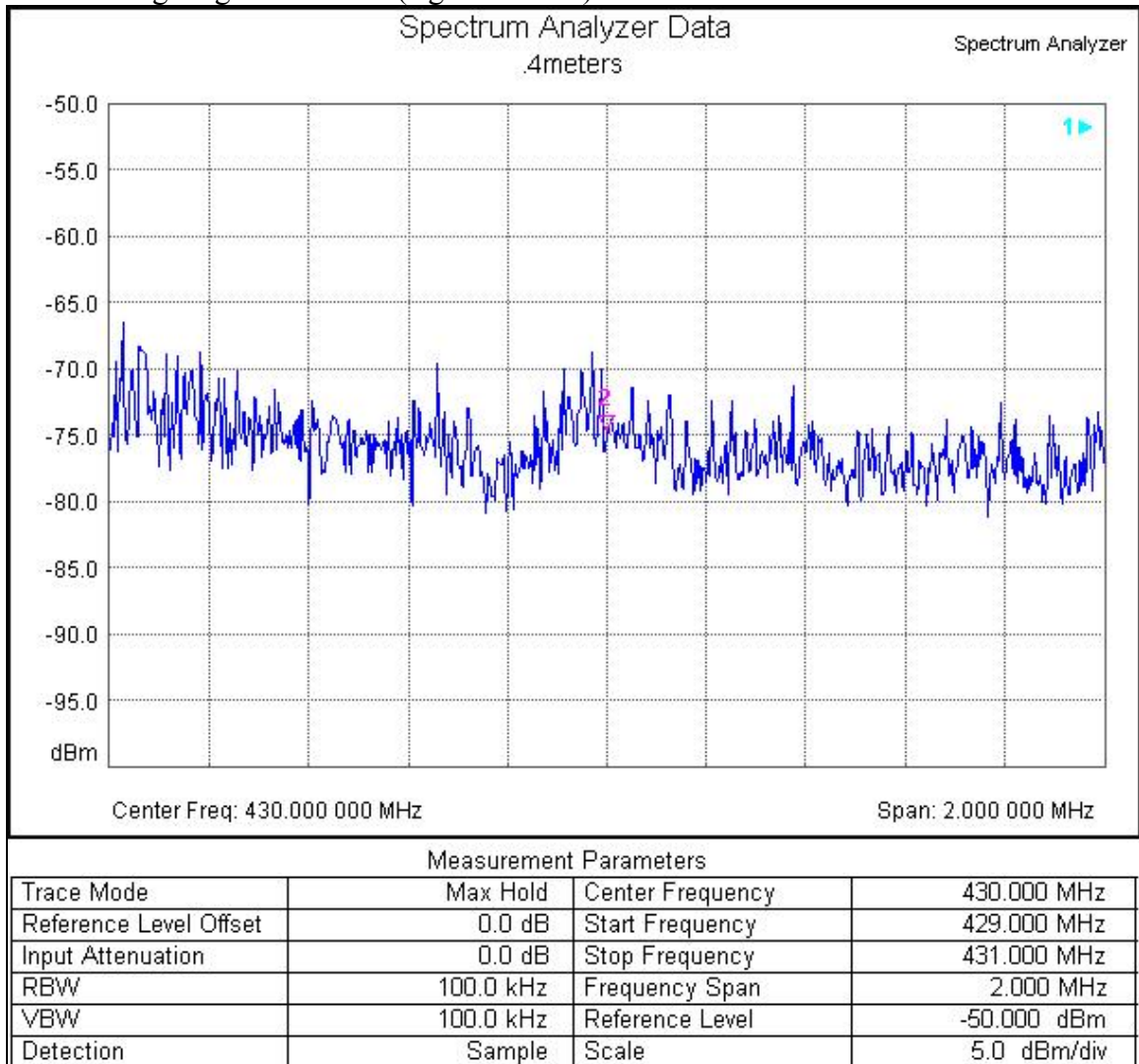


Figure 47. Spectrum analyzer at 400 meters from the transmitter.

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VI. APPLICATIONS

Potential applications are for:

- Personnel, vehicles, UAV tracking, and plotting the results on a 3D mapping engine in real time with great accuracy.
- Tracking aircraft in RADAR-denied or RADAR-impaired areas. For example, an aircraft can be tracked even if it flies behind mountains where ground-based RADAR or even airborne RADAR cannot detect it due to the mountain “shadow” or the earth’s curvature. This application relies on the special characteristics whereby specific wavelengths (UHF and VHF) can bend and reach areas behind terrain obstacles.
- Positional data can be shared among a formation, so each member can visualize the location of every individual asset in his or other formations. For example, a composite air-operation leader can increase his situational awareness by knowing the exact location of every aircraft under his command and even aircraft of other formations. This also applies to command and control centers as a situation awareness aid.
- The application can be used during flying training so pilots on the ground can visualize, in a 3D environment and in real time, the tracks and maneuvers of the airborne formations. It can also be used during debriefing training as an accurate representation (replay) of actual set-ups.
- Several airfields, especially the smaller ones, and tactical ranges can be equipped with an inexpensive APRS receiver and provide air traffic control to APRS-equipped aircraft. With the GeoFence feature the air traffic controller can be alerted with a sound or message box when an APRS-equipped aircraft enters or exits a predefined area or areas.
- A very important APRS application is on military or civilian search and rescue (SAR) operations when the location of a downed aircrew, for

example, can be determined immediately with great accuracy and encrypted. The 3-dimentionall representation will improve the perspective of the rescue teams.

- APRS devices can also be combined with other sensors, such as ground unattended perimeter coverage sensors or GPS-steered cameras that increase the SA.

VII. CONCLUSION AND FUTURE WORK

A. CONCLUSION

After conducting several lab and field experiments we reached the following conclusions.

An APRS network can be used to exchange positional data in local or spatially separated networks. It is scalable, meaning new nodes can be added at any time and several smaller networks can be combined to form a network that covers a wide area. Various data sources also can be combined, each time facilitating various sensors.

The use of digipeaters can extend the range of such a network up to hundreds of miles, until the data can be received from an I-Gate and distributed further to any location in the world. By fusing these positional data to a three-dimensional mapping system, increased situational awareness is achieved. It is much easier for the end user to perceive the big picture in 3D, rather than having to plot the received data in a two-dimensional environment.

Other data bases, for example, for real-time weather, cloud coverage, and real-time image-draping over the terrain, can help operators expedite the decision-making process. By combining all this information on a single screen and in a geo-referenced manner, the system becomes ultra-portable and can be rapidly deployed. When operating under certain frequencies, other features such as encryption can be added to make the data exchange less susceptible to interception by third parties.

Finally, the cost for building an APRS network as we see on Table 1 is relatively small because the mechanism for parsing and transmitting positional data uses inexpensive components developed mostly by the amateur radio community over the years.

B. FUTURE WORK

Use VHF frequencies to further extend the range of the network. During our tests, we found that due to the poor shielding of the handheld radios that we used, RF energy leakages from the laptop microprocessors interfered with the radio receiver component. This prevented us from using these frequency ranges without also using special cables from better shielded radios. By solving these issues, we could extend the coverage of our network much further.

Build a 3D mapping engine capable of rendering 3D objects in real time. Currently, NASAs World Wind uses Microsoft's direct-X rendering technique, thus making the import of 3D objects cumbersome. It is estimated that a Java version would resolve this issue.

Integrate a sensor reference system independent of the GPS infrastructure. Such a system would provide coverage in GPS-denied or -impaired areas, like mines or urban canyons. Inertial navigation systems or time-of-arrival (TOA) algorithms can be used to develop such a system.

Integrate GPS-equipped GSM radio modules for parsing and transmitting positional data in an SMS manner, so the system will use the existing worldwide cellular coverage.

Investigate further the interference that caused by high voltage power lines and prevented the APRS transmissions.

APPENDICES: DATA COLLECTION

APPENDIX A. KENWOOD TH-7D/BEYOND LOS

UNIT1>SUTRYS,WIDE2-2:`0IrlJ_K\>"7!}
UNIT1>SUTRYQ,WIDE2-2:`0Imlq0K\>"6v}
UNIT1>SUTRXW,WIDE2-2:`0Ikml.K\>"6r}
UNIT1>SUTRXQ,WIDE2-2:`0InnJ/K\>"6r}
UNIT1>SUTRWW,WIDE2-2:`0IvnrFK\>"6r}
UNIT1>SUTRWP,WIDE2-2:`0J"o@FK\>"6s}
UNIT1>SUTRVX,WIDE2-2:`0Jlo,aK\>"6t}
UNIT1>SUTRVX,WIDE2-2:`0J;n|bK\>"6z}
UNIT1>SUTRWT,WIDE2-2:`0JCnA<K\>"7"}
UNIT1>SUTRXU,WIDE2-2:`0JKo7CK\>"7#}
UNIT1>SUTRYY,WIDE2-2:`0JLo#WK\>"6y}
UNIT1>SUTSPX,WIDE2-2:`0JLo>_K\>"6w}
UNIT1>SUTSRQ,WIDE2-2:`0JKnH_K\>"6w}
UNIT1>SUTSRY,WIDE2-2:`0JOnALK\>"7!}
UNIT1>SUTSSQ,WIDE2-2:`0JXnhoK\>"7!}
UNIT1>SUTSTS,WIDE2-2:`0Juo-#K\>"7\$}
UNIT1>SUTSTY,WIDE2-2:`0J{ns2K\>"7'}
UNIT1>SUTSUS,WIDE2-2:`0K#n|}K\>"7'}
UNIT1>SUTSWT,WIDE2-2:`0K!nsDK\>"7!}
UNIT1>SUTRXQ,WIDE2-2:`0Jknq_K\>"6p}
UNIT1>SUTRXP,WIDE2-2:`0Jhl!1K\>"6z}
UNIT1>SUTRWP,WIDE2-2:`0J^ngIK\>"7*}
UNIT1>SUTRVW,WIDE2-2:`0JQnpK\>"7-}
UNIT1>SUTRVW,WIDE2-2:`0JFn>tK\>"7+}
UNIT1>SUTRVX,WIDE2-2:`0J?m?7K\>"7+}
UNIT1>SUTRUY,WIDE2-2:`0JAn5zK\>"7*}
UNIT1>SUTRSX,WIDE2-2:`0J>nqOK\>"7*}
UNIT1>SUTRST,WIDE2-2:`0J8nSAK\>"7%}
UNIT1>SUTRST,WIDE2-2:`0J8l!?K\>"7!}
UNIT1>SUTRSS,WIDE2-2:`0J8l!?K\>"6y}
UNIT1>SUTRSS,WIDE2-2:`0J8l!?K\>"6w}
UNIT1>SUTRSP,WIDE2-2:`0J.nq\$K\>"6z}
UNIT1>SUTRRV,WIDE2-2:`0J nq#K\>"7"}
UNIT1>SUTRQX,WIDE2-2:`0J_mgdK\>"7\$}
UNIT1>SUTQXX,WIDE2-2:`0IhlS,K\>"6o}
UNIT1>SUTQYP,WIDE2-2:`0Ijl\%K\>"6q}
UNIT1>SUTQYW,WIDE2-2:`0Irl#/K\>"6t}
UNIT1>SUTQYU,WIDE2-2:`0Iql!DK\>"6o}
UNIT1>SUTQYW,WIDE2-2:`0Ism_/K\>"6r}

UNIT1>SUTRPS,WIDE2-2: `0IxmU,K\>"6s}
 UNIT1>SUTQYP,WIDE2-2: `0Iim]?K\>"6s}
 UNIT1>SUTQXU,WIDE2-2: `0Iem+AK\>"6r}
 UNIT1>SUTQUY,WIDE2-2: `0INn]FK\>"6f}
 UNIT1>SUTQTP,WIDE2-2: `0lin@GK\>"6b}
 UNIT1>SUTQSS,WIDE2-2: `0Iul"DK\>"6f}
 UNIT1>SUTQSS,WIDE2-2: `0J_n"tK\>"6l}
 UNIT1>SUTQSR,WIDE2-2: `0J@l"IK\>"6y}
 UNIT1>SUTQSS,WIDE2-2: `0JalreK\>"7'}
 UNIT1>SUTQSS,WIDE2-2: `0Jl"uK\>"7,}
 UNIT1>SUTQTS,WIDE2-2: `0K7l#2K\>"7+}
 UNIT1>SUTQTS,WIDE2-2: `0K7l_2K\>"7,}
 UNIT1>SUTQTU,WIDE2-2: `0K9m#>K\>"7-}
 UNIT1>SUTQTW,WIDE2-2: `0K:!!_K\>"7+}
 UNIT1>SUTQTV,WIDE2-2: `0K<l IK\>"7.}
 UNIT1>SUTQTW,WIDE2-2: `0K>IU5K\>"72}
 UNIT1>SUTQUP,WIDE2-2: `0K<IR%K\>"75}
 UNIT1>SUTQUX,WIDE2-2: `0K?l_@K\>"7D}
 UNIT1>SUTQVU,WIDE2-2: `0KEl}3K\>"7\}
 UNIT1>SUTQVV,WIDE2-2: `0KFIA>K\>"7'}
 UNIT1>SUTQWV,WIDE2-2: `0K0mJzK\>"7u}
 UNIT1>SUTQWW,WIDE2-2: `0KSm"nK\>"7y}
 UNIT1>SUTQWX,WIDE2-2: `0KYm"xK\>"8,}
 UNIT1>SUTQXQ,WIDE2-2: `0K[ms%K\>"83}
 UNIT1>SUTQXQ,WIDE2-2: `0K]l#_K\>"85}
 UNIT1>SUTQXS,WIDE2-2: `0K_m# K\>"88}
 UNIT1>SUTQXW,WIDE2-2: `0Kkm#%K\>"88}
 UNIT1>SUTQXX,WIDE2-2: `0Kom"pK\>"89}
 UNIT1>SUTQXW,WIDE2-2: `0Kvn"eK\>"8@}
 UNIT1>SUTQYQ,WIDE2-2: `0L_ms!K\>"8F}
 UNIT1>SUTQYT,WIDE2-2: `0L_mA0K\>"8M}
 UNIT1>SUTQYX,WIDE2-2: `0L\$mU+K\>"8S}
 UNIT1>SUTRPS,WIDE2-2: `0L*mU,K\>"8n}
 UNIT1>SUTRPW,WIDE2-2: `0L.mK6K\>"8v}
 UNIT1>SUTRQP,WIDE2-2: `0L0mK:K\>"9\$}
 UNIT1>SUTRQV,WIDE2-2: `0L5mU2K\>"93}
 UNIT1>SUTRQY,WIDE2-2: `0L8l_-K\>"9,}
 UNIT1>SUTRRP,WIDE2-2: `0L8lA3K\>"9@}
 UNIT1>SUTRRR,WIDE2-2: `0L9liMK\>"9K}
 UNIT1>SUTRRS,WIDE2-2: `0L8l^~K\>"9I}
 UNIT1>SUTRRQ,WIDE2-2: `0L9lSrK\>"9L}
 UNIT1>SUTRRR,WIDE2-2: `0L;ls,K\>"9P}
 UNIT1>SUTRRU,WIDE2-2: `0L>l}NK\>"9Q}
 UNIT1>SUTRRX,WIDE2-2: `0LBm,□K\>"9R}
 UNIT1>SUTRRY,WIDE2-2: `0LEm6xK\>"9T}

UNIT1>SUTRSR,WIDE2-2:`0LKmJuK\>"9U}
 UNIT1>SUTRSR,WIDE2-2:`0LNI"oK\>"9V}
 UNIT1>SUTRSS,WIDE2-2:`0LOl6rK\>"9U}
 UNIT1>SUTRST,WIDE2-2:`0LTm6lK\>"9N}
 UNIT1>SUTRSS,WIDE2-2:`0LWlfPK\>"9C}
 UNIT1>SUTRST,WIDE2-2:`0LTI>`K\>"9K}
 UNIT1>SUTRSS,WIDE2-2:`0LTI5^K\>"9L}
 UNIT1>SUTRST,WIDE2-2:`0LTI>K\>"9K}
 UNIT1>SUTRSS,WIDE2-2:`0LPm+"K\>"9N}
 UNIT1>SUTRSR,WIDE2-2:`0LJm+ K\>"9P}
 UNIT1>SUTRRY,WIDE2-2:`0LCmS0K\>"9T}
 UNIT1>SUTRRW,WIDE2-2:`0L?ml(K\>"9S}
 UNIT1>SUTRRW,WIDE2-2:`0L>l+4K\>"9R}
 UNIT1>SUTRRW,WIDE2-2:`0L;lzqK\>"9Q}
 UNIT1>SUTRRV,WIDE2-2:`0L9lf□K\>"9Q}
 UNIT1>SUTRRV,WIDE2-2:`0L9lJsK\>"9P}
 UNIT1>SUTRRW,WIDE2-2:`0L<lTnK\>"9P}
 UNIT1>SUTRRW,WIDE2-2:`0L=lA.K\>"9O}
 UNIT1>SUTRRT,WIDE2-2:`0L=m?KK\>"9N}
 UNIT1>SUTRRR,WIDE2-2:`0L9m!_K\>"9K}
 UNIT1>SUTRRT,WIDE2-2:`0L4m*vK\>"9I}
 UNIT1>SUTRRT,WIDE2-2:`0L0m*sK\>"9J}
 UNIT1>SUTRRW,WIDE2-2:`0L+m>7K\>"9C}
 UNIT1>SUTRRX,WIDE2-2:`0L&m*~K\>"9=}
 UNIT1>SUTRRX,WIDE2-2:`0L\$15_K\>"93}
 UNIT1>SUTRRW,WIDE2-2:`0L"l4xK\>"9)}
 UNIT1>SUTRRW,WIDE2-2:`0L!l yK\>"9'}
 UNIT1>SUTRRW,WIDE2-2:`0L!l uK\>"9&}
 UNIT1>SUTRRW,WIDE2-2:`0L l bK\>"9\$}
 UNIT1>SUTRRW,WIDE2-2:`0L l bK\>"9"}
 UNIT1>SUTRRW,WIDE2-2:`0L l bK\>"8{
 UNIT1>SUTRRW,WIDE2-2:`0L l bK\>"8{
 UNIT1>SUTRRW,WIDE2-2:`0L_lzJK\>"8x}
 UNIT1>SUTRSS,WIDE2-2:`0K□m>5K\>"8n}
 UNIT1>SUTRSU,WIDE2-2:`0L_ls2K\>"8g}
 UNIT1>SUTRSW,WIDE2-2:`0L_ls1K\>"8c}
 UNIT1>SUTRTS,WIDE2-2:`0L!mAJK\>"8`}
 UNIT1>SUTRTV,WIDE2-2:`0L"mKEK\>"8^}
 UNIT1>SUTRUQ,WIDE2-2:`0L%n-6K\>"8]}
 UNIT1>SUTRUU,WIDE2-2:`0L\$lf.K\>"8E}
 UNIT1>SUTRUW,WIDE2-2:`0L"lzPK\>"88}
 UNIT1>SUTRWQ,WIDE2-2:`0Kmm4[K\>"7_}
 UNIT1>SUTRWQ,WIDE2-2:`0Kml WK\>"7'}
 UNIT1>SUTRWR,WIDE2-2:`0Kkm*WK\>"7^}
 UNIT1>SUTRWW,WIDE2-2:`0KdmfXK\>"7^}

UNIT1>SUTRXP,WIDE2-2:`0K]n*LK\>"7a}
 UNIT1>SUTRXT,WIDE2-2:`0KUmR@K\>"7b}
 UNIT1>SUTRXU,WIDE2-2:`0KQlpxK\>"7k}
 UNIT1>SUTRXU,WIDE2-2:`0KOl>IK\>"7j}
 UNIT1>SUTRXU,WIDE2-2:`0KNIHfK\>"7h}
 UNIT1>SUTRXW,WIDE2-2:`0KKIRKK\>"7c}
 UNIT1>SUTRYS,WIDE2-2:`0KHn>+K\>"7^}
 UNIT1>SUTRYX,WIDE2-2:`0KFm>2K\>"7U}
 UNIT1>SUTSPS,WIDE2-2:`0KCm*1K\>"7A}
 UNIT1>SUTSPU,WIDE2-2:`0K2mS8K\>"6r}
 UNIT1>SUTSPT,WIDE2-2:`0K/l?8K\>"6l}
 UNIT1>SUTSPQ,WIDE2-2:`0K)n5.K\>"6l}
 UNIT1>SUTRXX,WIDE2-2:`0Jxn{FK\>"6r}
 UNIT1>SUTRWY,WIDE2-2:`0Jen{@K\>"6w}
 UNIT1>SUTRVY,WIDE2-2:`0J\n{IK\>"7+}
 UNIT1>SUTRVW,WIDE2-2:`0JMo\vK\>"7)}
 UNIT1>SUTRVX,WIDE2-2:`0JAo qK\>"7\$}
 UNIT1>SUTRVX,WIDE2-2:`0J0o uK\>"6z}
 UNIT1>SUTRWQ,WIDE2-2:`0J_4ZK\>"6w}
 UNIT1>SUTRWV,WIDE2-2:`0IvozZK\>"6v}
 UNIT1>SUTRXV,WIDE2-2:`0Ikn\6K\>"6r}
 UNIT1>SUTRYQ,WIDE2-2:`0IImK"K\>"6r}
 UNIT1>SUTRYS,WIDE2-2:`0Iqm#)K\>"6r}
 UNIT1>SUTRYT,WIDE2-2:`0IqlIGK\>"6u}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"6y}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7"}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7#}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7#}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7&}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7)}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7,}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7-}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7+}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7({
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7)}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7)}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!GK\>"7)}

APPENDIX B. KENWOOD TH-7D/ LOS

UNIT1>SUTRYT,WIDE2-2:`0Iql,{K\>"6\}
UNIT1>SUTRYT,WIDE2-1:`0Iql,{K\>"6\}
UNIT1>SUTRYT,WIDE2-2:`0Irl6&K\>"6\}
UNIT1>SUTRYT,WIDE2-1:`0Irl6&K\>"6\}
UNIT1>SUTRYS,WIDE2-2:`0Iqlg_K\>"6\}
UNIT1>SUTRYS,WIDE2-1:`0Iqlg_K\>"6\}
UNIT1>SUTRYQ,WIDE2-2:`0Inlg2K\>"6\}
UNIT1>SUTRYQ,WIDE2-1:`0Inlg2K\>"6\}
UNIT1>SUTRXX,WIDE2-2:`0Iklq/K\>"6\}
UNIT1>SUTRXX,WIDE2-1:`0Iklq/K\>"6\}
UNIT1>SUTRXU,WIDE2-2:`0IlmI|K\>"6\}
UNIT1>SUTRXU,WIDE2-1:`0IlmI|K\>"6\}
UNIT1>SUTRWY,WIDE2-2:`0IqmrEK\>"6\}
UNIT1>SUTRWY,WIDE2-1:`0IqmrEK\>"6\}
UNIT1>SUTRWU,WIDE2-2:`0Izn"GK\>"6a\}
UNIT1>SUTRWU,WIDE2-1:`0Izn"GK\>"6a\}
UNIT1>SUTRWS,WIDE2-2:`0J_n"FK\>"6\}
UNIT1>SUTRWS,WIDE2-1:`0J_n"FK\>"6\}
UNIT1>SUTRVY,WIDE2-2:`0J'n,QK\>"6a\}
UNIT1>SUTRVY,WIDE2-1:`0J'n,QK\>"6a\}
UNIT1>SUTRVX,WIDE2-2:`0J.n6bK\>"6e\}
UNIT1>SUTRVX,WIDE2-1:`0J.n6bK\>"6e\}
UNIT1>SUTRVX,WIDE2-2:`0J8n,bK\>"6u\}
UNIT1>SUTRVX,WIDE2-1:`0J8n,bK\>"6u\}
UNIT1>SUTRWP,WIDE2-2:`0J@mK>K\>"6v\}
UNIT1>SUTRWP,WIDE2-1:`0J@mK>K\>"6v\}
UNIT1>SUTRWT,WIDE2-2:`0JCmi:K\>"6v\}
UNIT1>SUTRWT,WIDE2-1:`0JCmi:K\>"6v\}
UNIT1>SUTRXP,WIDE2-2:`0JGms9K\>"7\}
UNIT1>SUTRXP,WIDE2-1:`0JGms9K\>"7\}
UNIT1>SUTRXY,WIDE2-1:`0JKn-UK\>"7\$\}
UNIT1>SUTRYU,WIDE2-2:`0JKn#WK\>"7!\}
UNIT1>SUTRYU,WIDE2-1:`0JKn#WK\>"7!\}
UNIT1>SUTSPR,WIDE2-2:`0JKmsWK\>"6\}
UNIT1>SUTSPR,WIDE2-1:`0JKmsWK\>"6\}
UNIT1>SUTSQQ,WIDE2-2:`0JKm}VK\>"6y\}
UNIT1>SUTSQQ,WIDE2-1:`0JKm}VK\>"6y\}
UNIT1>SUTSQV,WIDE2-2:`0JKmf_K\>"6y\}
UNIT1>SUTSQV,WIDE2-1:`0JKmf_K\>"6y\}
UNIT1>SUTSRS,WIDE2-2:`0JKmf_K\>"7#\}
UNIT1>SUTSRS,WIDE2-1:`0JKmf_K\>"7#\}
UNIT1>SUTSRX,WIDE2-2:`0JMmA#K\>"7%\}
UNIT1>SUTSRX,WIDE2-1:`0JMmA#K\>"7%\}
UNIT1>SUTSRY,WIDE2-1:`0JRhjK\>"7#\}

UNIT1>SUTSSR,WIDE2-1: `0JZn,wK\>"6w}
 UNIT1>SUTSSU,WIDE2-1: `0Jdn,xK\>"6v}
 UNIT1>SUTSSW,WIDE2-2: `0Jkn6xK\>"6t}
 UNIT1>SUTSSW,WIDE2-1: `0Jkn6xK\>"6t}
 UNIT1>SUTSTR,WIDE2-2: `0Jsn#)K\>"6w}
 UNIT1>SUTSTR,WIDE2-1: `0Jsn#)K\>"6w}
 UNIT1>SUTSTX,WIDE2-1: `0Jzm}#K\>"6{}
 UNIT1>SUTSUP,WIDE2-1: `0K_n,uK\>"7!}
 UNIT1>SUTSUT,WIDE2-1: `0K&n,~K\>"7"}
 UNIT1>SUTSVR,WIDE2-1: `0K+m}IK\>"7&}
 UNIT1>SUTSVV,WIDE2-1: `0K(mzVK\>"7'}
 UNIT1>SUTSVY,WIDE2-1: `0K n `K\>"7#}
 UNIT1>SUTSWU,WIDE2-1: `0K!n#>K\>"7'}
 UNIT1>SUTSXT,WIDE2-1: `0K&n7<K\>"7,}
 UNIT1>SUTSYQ,WIDE2-1: `0K)n#DK\>"77}
 UNIT1>SUTSYW,WIDE2-1: `0K+l}5K\>"7;}
 UNIT1>SUTSYW,WIDE2-1: `0K,l#3K\>"7;}
 UNIT1>SUTSYX,WIDE2-1: `0K,l#5K\>"7:}
 UNIT1>SUTTPS,WIDE2-1: `0K0n76K\>"73}
 UNIT1>SUTTQS,WIDE2-1: `0K0nH)K\>"71}
 UNIT1>SUTTRR,WIDE2-1: `0K-n4*K\>"76}
 UNIT1>SUTTRX,WIDE2-1: `0K,n>*K\>"7;}
 UNIT1>SUTTSW,WIDE2-1: `0K-n#6K\>"7<}
 UNIT1>SUTTTR,WIDE2-1: `0K2m}9K\>"7=}
 UNIT1>SUTTTS,WIDE2-1: `0K3l79K\>"7@}
 UNIT1>SUTTTS,WIDE2-1: `0K3l#9K\>"7C}
 UNIT1>SUTTTY,WIDE2-1: `0K=n@wK\>"70}
 UNIT1>SUTTUV,WIDE2-1: `0KHni%K\>"7%}
 UNIT1>SUTTVQ,WIDE2-1: `0KRnJvK\>"6w}
 UNIT1>SUTTVW,WIDE2-1: `0KS n#RK\>"6x}
 UNIT1>SUTTWV,WIDE2-1: `0KUn-:K\>"6u}
 UNIT1>SUTTXQ,WIDE2-1: `0K\n-*K\>"6h}
 UNIT1>SUTTXV,WIDE2-1: `0K`n#=#K\>"6h}
 UNIT1>SUTTYU,WIDE2-1: `0KfnK9K\>"6f}
 UNIT1>SUTUPS,WIDE2-1: `0Kfn4"K\>"6k}
 UNIT1>SUTUPY,WIDE2-1: `0Kfmz_K\>"6h}
 UNIT1>SUTUQV,WIDE2-1: `0KnnADK\>"6^}
 UNIT1>SUTURU,WIDE2-1: `0KonAWK\>"6S}
 UNIT1>SUTUSR,WIDE2-1: `0Knn>%K\>"6M}
 UNIT1>SUTUTP,WIDE2-1: `0KrnA(K\>"6E}
 UNIT1>SUTUTU,WIDE2-1: `0K{nJ~K\>"60}
 UNIT1>SUTUUQ,WIDE2-1: `0K|n*_K\>"6-}
 UNIT1>SUTUWX,WIDE2-1: `0Kcmp(K\>"6%}
 UNIT1>SUTUXT,WIDE2-1: `0Kfmi,K\>"6#}
 UNIT1>SUTUYQ,WIDE2-1: `0Knn-0K\>"6!}

UNIT1>SUTUYU,WIDE2-1:`0Krn-1K\>"5z}
 UNIT1>SUTVPR,WIDE2-1:`0Kxm}1K\>"5u}
 UNIT1>SUTVPY,WIDE2-1:`0Kwm4+K\>"5w}
 UNIT1>SUTVQQ,WIDE2-1:`0KulHVK\>"5{}
 UNIT1>SUTVQS,WIDE2-1:`0Ksl\LK\>"5x}
 UNIT1>SUTVRP,WIDE2-1:`0KinH?K\>"5x}
 UNIT1>SUTVRV,WIDE2-1:`0KenH8K\>"5w}
 UNIT1>SUTVST,WIDE2-1:`0K_n>7K\>"5u}
 UNIT1>SUTVTS,WIDE2-1:`0KYn>8K\>"5u}
 UNIT1>SUTVTY,WIDE2-1:`0KVn48K\>"5u}
 UNIT1>SUTVUW,WIDE2-1:`0KPn>9K\>"5t}
 UNIT1>SUTVVV,WIDE2-1:`0KJn49K\>"5s}
 UNIT1>SUTVWQ,WIDE2-1:`0KGn*9K\>"5q}
 UNIT1>SUTVWY,WIDE2-1:`0KBn44K\>"5s}
 UNIT1>SUTVXX,WIDE2-1:`0K=n*2K\>"5t}
 UNIT1>SUTVYS,WIDE2-1:`0K:n*<K\>"5t}
 UNIT1>SUTWPP,WIDE2-1:`0K5n4<K\>"5p}
 UNIT1>SUTWPY,WIDE2-1:`0K.n><K\>"5m}
 UNIT1>SUTWQT,WIDE2-1:`0K*n>>K\>"5l}
 UNIT1>SUTWRQ,WIDE2-1:`0K#n IK\>"5k}
 UNIT1>SUTWRW,WIDE2-1:`0J~n4CK\>"5l}
 UNIT1>SUTWSS,WIDE2-1:`0JznH7K\>"5l}
 UNIT1>SUTWTQ,WIDE2-1:`0Jtn>7K\>"5m}
 UNIT1>SUTWTW,WIDE2-1:`0Jqn>8K\>"5n}
 UNIT1>SUTWUV,WIDE2-1:`0Jjn>AK\>"5p}
 UNIT1>SUTWVR,WIDE2-1:`0JanHUK\>"5r}
 UNIT1>SUTWVT,WIDE2-1:`0JZnH^K\>"5r}
 UNIT1>SUTWVY,WIDE2-1:`0JMnR_K\>"5p}
 UNIT1>SUTWWS,WIDE2-1:`0JBnH^K\>"5q}
 UNIT1>SUTWWV,WIDE2-1:`0J-nHxK\>"5p}
 UNIT1>SUTWWQ,WIDE2-1:`0I^nI_K\>"5l}
 UNIT1>SUTWWS,WIDE2-1:`0ISn*YK\>"5s}
 UNIT1>SUTWUQ,WIDE2-1:`0HumqBK\>"6!}
 UNIT1>SUTWRR,WIDE2-1:`0HYn5DK\>"6%}
 UNIT1>SUTWPR,WIDE2-1:`0HDn5DK\>"6({
 UNIT1>SUTVYV,WIDE2-1:`0H>mqCK\>"6*}
 UNIT1>SUTVYU,WIDE2-1:`0H=!!?K\>"6*}
 UNIT1>SUTVXW,WIDE2-1:`0H>m{vK\>"6)}
 UNIT1>SUTVWX,WIDE2-1:`0H?n?uK\>"6\$}
 UNIT1>SUTVWS,WIDE2-1:`0H=n+PK\>"6&}
 UNIT1>SUTVVS,WIDE2-1:`0H:n?jK\>"6)}
 UNIT1>SUTVUU,WIDE2-1:`0H:n+IK\>"6+}
 UNIT1>SUTVTY,WIDE2-1:`0H;n?rK\>"6*}
 UNIT1>SUTVTP,WIDE2-1:`0H<n+iK\>"6*}
 UNIT1>SUTVST,WIDE2-1:`0H:n5]K\>"6,}

UNIT1>SUTVRV,WIDE2-1:`0H8n+`K\>"62}
 UNIT1>SUTVQW,WIDE2-1:`0H9n!wK\>"63}
 UNIT1>SUTVQQ,WIDE2-1:`0H:n+wK\>"64}
 UNIT1>SUTVPS,WIDE2-1:`0H<n+vK\>"67}
 UNIT1>SUTUYS,WIDE2-1:`0H;nIYK\>"64}
 UNIT1>SUTUXW,WIDE2-1:`0H7n?JK\>"63}
 UNIT1>SUTUWY,WIDE2-1:`0H1n5FK\>"6<}
 UNIT1>SUTUWQ,WIDE2-1:`0H)n5GK\>"6>}
 UNIT1>SUTUVV,WIDE2-1:`0H%nIGK\>"6=}
 UNIT1>SUTUUX,WIDE2-1:`0H_nIHK\>"6>}
 UNIT1>SUTUTY,WIDE2-1:`0GynSGK\>"6?}
 UNIT1>SUTUTS,WIDE2-1:`0Gun?TK\>"6A}
 UNIT1>SUTUST,WIDE2-1:`0Gun?qK\>"6<}
 UNIT1>SUTURT,WIDE2-1:`0GvnItK\>"68}
 UNIT1>SUTUQW,WIDE2-1:`0Gwn!sK\>"6:}
 UNIT1>SUTUPY,WIDE2-1:`0Gyn+xK\>"6<}
 UNIT1>SUTTTY,Y,WIDE2-1:`0G|n?yK\>"6<}
 UNIT1>SUTTYS,WIDE2-1:`0G}n!IK\>"6@}
 UNIT1>SUTTXU,WIDE2-1:`0G|n!cK\>"6F}
 UNIT1>SUTTWU,WIDE2-1:`0Gzn+dK\>"6F}
 UNIT1>SUTTWP,WIDE2-1:`0G{m|0K\>"6J}
 UNIT1>SUTTVV,WIDE2-1:`0H n6IK\>"6P}
 UNIT1>SUTTVU,WIDE2-1:`0H`n"VK\>"6R}
 UNIT1>SUTTVV,WIDE2-1:`0H4n@aK\>"6N}
 UNIT1>SUTTVP,WIDE2-1:`0H;n@,K\>"6N}
 UNIT1>SUTTUS,WIDE2-1:`0H;nSIK\>"6Q}
 UNIT1>SUTTTY,WIDE2-1:`0HDm|nK\>"6V}
 UNIT1>SUTTUR,WIDE2-1:`0HNN6vK\>"6S}
 UNIT1>SUTTUP,WIDE2-1:`0HUn6KK\>"6R}
 UNIT1>SUTTTT,WIDE2-1:`0H^`n,2K\>"6U}
 UNIT1>SUTTSQ,WIDE2-1:`0H`n+SK\>"6\}
 UNIT1>SUTTRR,WIDE2-1:`0H_m{xK\>"6_}
 UNIT1>SUTTQW,WIDE2-1:`0Hdmh8K\>"6h}
 UNIT1>SUTTQU,WIDE2-1:`0Hwm^VK\>"7&}
 UNIT1>SUTTQV,WIDE2-1:`0I"m|IK\>"77}
 UNIT1>SUTTQT,WIDE2-1:`0I*mh@K\>"7C}
 UNIT1>SUTTPP,WIDE2-1:`0I.n5cK\>"7=}
 UNIT1>SUTSYR,WIDE2-2:`0I0n+{K\>"7:}
 UNIT1>SUTSYR,WIDE2-1:`0I0n+{K\>"7:}
 UNIT1>SUTSXW,WIDE2-2:`0I5n@1K\>"76}
 UNIT1>SUTSXW,WIDE2-1:`0I5n@1K\>"76}
 UNIT1>SUTSWX,WIDE2-2:`0I;n@!K\>"71}
 UNIT1>SUTSWX,WIDE2-1:`0I;n@!K\>"71}
 UNIT1>SUTSVY,WIDE2-1:`0I?n6_K\>"7,}
 UNIT1>SUTSVS,WIDE2-2:`0I?n+aK\>"7-}

UNIT1>SUTSVS,WIDE2-1:`0I?n+aK\>"7-}
 UNIT1>SUTSUS,WIDE2-1:`0I;nSZK\>"7.}
 UNIT1>SUTSTS,WIDE2-2:`0I7nSZK\>"7,}
 UNIT1>SUTSTS,WIDE2-1:`0I7nSZK\>"7,}
 UNIT1>SUTSSW,WIDE2-2:`0I5nI]K\>"7+}
 UNIT1>SUTSSW,WIDE2-1:`0I5nI]K\>"7+}
 UNIT1>SUTSRV,WIDE2-2:`0I5n?wK\>"7%}
 UNIT1>SUTSRV,WIDE2-1:`0I5n?wK\>"7%}
 UNIT1>SUTSRP,WIDE2-2:`0I;m|<K\>"6x}
 UNIT1>SUTSQV,WIDE2-2:`0IA nJ=K\>"6t}
 UNIT1>SUTSQV,WIDE2-1:`0IA nJ=K\>"6t}
 UNIT1>SUTSPU,WIDE2-2:`0IRnJ=K\>"6o}
 UNIT1>SUTSPU,WIDE2-1:`0IRnJ=K\>"6o}
 UNIT1>SUTSPP,WIDE2-2:`0I[n6<K\>"6m}
 UNIT1>SUTSPP,WIDE2-1:`0I[n6<K\>"6m}
 UNIT1>SUTRYT,WIDE2-2:`0Idn"<K\>"6l}
 UNIT1>SUTRYT,WIDE2-1:`0Idn"<K\>"6l}
 UNIT1>SUTRYQ,WIDE2-2:`0Iimr7K\>"6l}
 UNIT1>SUTRYQ,WIDE2-1:`0Iimr7K\>"6l}
 UNIT1>SUTRYP,WIDE2-2:`0Imls_K\>"6k}
 UNIT1>SUTRYP,WIDE2-1:`0Imls_K\>"6k}
 UNIT1>SUTRYS,WIDE2-2:`0Iqlr~K\>"6j}
 UNIT1>SUTRYS,WIDE2-1:`0Iqlr~K\>"6j}
 UNIT1>SUTRYT,WIDE2-2:`0Irl\,K\>"6i}
 UNIT1>SUTRYT,WIDE2-1:`0Irl\,K\>"6i}
 UNIT1>SUTRYT,WIDE2-2:`0Ipl]SK\>"6p}
 UNIT1>SUTRYT,WIDE2-1:`0Ipl]SK\>"6p}
 UNIT1>SUTRYT,WIDE2-2:`0Ipl!VK\>"6r}
 UNIT1>SUTRYT,WIDE2-1:`0Ipl!VK\>"6r}
 UNIT1>SUTRYT,WIDE2-2:`0Ipl!VK\>"6s}
 UNIT1>SUTRYT,WIDE2-1:`0Ipl!VK\>"6s}
 UNIT1>SUTRYT,WIDE2-2:`0Ipl!VK\>"6t}
 UNIT1>SUTRYT,WIDE2-1:`0Ipl!VK\>"6t}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6t}
 UNIT1>SUTRYT,WIDE2-1:`0Iql!VK\>"6t}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6u}
 UNIT1>SUTRYT,WIDE2-1:`0Iql!VK\>"6u}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6v}
 UNIT1>SUTRYT,WIDE2-1:`0Iql!VK\>"6v}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6v}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6u}
 UNIT1>SUTRYT,WIDE2-1:`0Iql!VK\>"6u}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6s}
 UNIT1>SUTRYT,WIDE2-1:`0Iql!VK\>"6s}
 UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6s}

UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6s}
UNIT1>SUTRYT,WIDE2-1:`0Iql!VK\>"6s}
UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6w}
UNIT1>SUTRYT,WIDE2-1:`0Iql!VK\>"6w}
UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6x}
UNIT1>SUTRYT,WIDE2-1:`0Iql!VK\>"6x}
UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6z}
UNIT1>SUTRYT,WIDE2-1:`0Iql!VK\>"6z}
UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6{}
UNIT1>SUTRYT,WIDE2-1:`0Iql!VK\>"6{}
UNIT1>SUTRYT,WIDE2-2:`0Iql!VK\>"6y}
UNIT1>SUTRYT,WIDE2-1:`0Iql!VK\>"6y}

APPENDIX C. KENWOOD TH-7D/MAX RANGE

UNIT1>SUTWYW,WIDE2-1:`0HRI#_K\>"3r}
UNIT1>SUTWYW,WIDE2-1:`0HRI#_K\>"6#}
UNIT1>SUTWYW,WIDE2-1:`0HRI#_K\>"6({
UNIT1>SUTWYW,WIDE2-1:`0HRI#_K\>"6.}
UNIT1>SUTWYW,WIDE2-1:`0HRI#_K\>"61}
UNIT1>SUTWYX,WIDE2-1:`0HRI#_K\>"64}
UNIT1>SUTWYX,WIDE2-1:`0HRI#_K\>"67}
UNIT1>SUTWYX,WIDE2-1:`0HRI#_K\>"6:}
UNIT1>SUTWYX,WIDE2-1:`0HRI#_K\>"69}
UNIT1>SUTWYX,WIDE2-1:`0HRI,rK\>"67}
UNIT1>SUTWYX,WIDE2-1:`0HSI" {K\>"62}
UNIT1>SUTWYX,WIDE2-1:`0HSI" {K\>"61}
UNIT1>SUTWYY,WIDE2-1:`0HTITvK\>"6.}
UNIT1>SUTXPU,WIDE2-1:`0H^o-(K\>"6-}
UNIT1>SUTXQW,WIDE2-1:`0Hj A6K\>"6"}
UNIT1>SUTXRY,WIDE2-1:`0Hr!-:K\>"5q}
UNIT1>SUTXUP,WIDE2-1:`0I_!_ ;K\>"5j}
UNIT1>SUTXWP,WIDE2-1:`0I)!_ =K\>"5g}
UNIT1>SUTXXT,WIDE2-1:`0I1!_ =K\>"5e}
UNIT1>SUTYPV,WIDE2-1:`0I>!_ =K\>"5`}
UNIT1>SUTYRV,WIDE2-1:`0IJ!_ >K\>"5a}
UNIT1>SUTYTP,WIDE2-1:`0IR!U@K\>"5d}
UNIT1>SUTYVT,WIDE2-1:`0IS!R\$K\>"5h}
UNIT1>SUTYXV,WIDE2-1:`0IO!#\K\>"5k}
UNIT1>SUUPPR,WIDE2-1:`0IM!#\K\>"5k}
UNIT1>SUUPRV,WIDE2-1:`0II!#\K\>"5j}
UNIT1>SUUPTX,WIDE2-1:`0IM!_LK\>"5j}
UNIT1>SUUPVQ,WIDE2-1:`0IV!_ :K\>"5h}
UNIT1>SUUQQW,WIDE2-1:`0J_!^nK\>"5d}
UNIT1>SUUQRV,WIDE2-1:`0K,!^nK\>"5c}
UNIT1>SUUQSQ,WIDE2-1:`0KF!^nK\>"5b}
UNIT1>SUUQST,WIDE2-1:`0KX!TnK\>"5b}
UNIT1>SUUQSQ,WIDE2-1:`0Kw!^WK\>"5d}
UNIT1>SUUQSR,WIDE2-1:`0L&!TpK\>"5d}
UNIT1>SUUQTT,WIDE2-1:`0L;!_ 'K\>"5c}
UNIT1>SUUQYS,WIDE2-1:`0M,!_ K\>"5p}
UNIT1>SUURPQ,WIDE2-1:`0M=!_ K\>"5p}
UNIT1>SUURQR,WIDE2-1:`0MT!_ K\>"5m}
UNIT1>SUURRU,WIDE2-1:`0Mn!_ K\>"5l}
UNIT1>SUURTY,WIDE2-1:`0N-!U,K\>"5\}
UNIT1>SUURWP,WIDE2-1:`0N<!_ @K\>"5]}
UNIT1>SUURXU,WIDE2-1:`0NC!U@K\>"5_}
UNIT1>SUUSPU,WIDE2-1:`0NL!UEK\>"5g}
UNIT1>SUUSSP,WIDE2-1:`0NM!_K\>"5i}

UNIT1>SUUSTV,WIDE2-1: `0NL!_K\>"5l}
 UNIT1>SUUSVW,WIDE2-1: `0NL!_K\>"5o}
 UNIT1>SUUSYR,WIDE2-1: `0NM!_RK\>"5p}
 UNIT1>SUUTPX,WIDE2-1: `0NP!UJK\>"5m}
 UNIT1>SUUTRX,WIDE2-1: `0NZ!_?K\>"5i}
 UNIT1>SUUTTY,WIDE2-1: `0Ni!_9K\>"5h}
 UNIT1>SUUTVR,WIDE2-1: `0Nt!U0K\>"5e}
 UNIT1>SUUUWY,WIDE2-1: `0P0!UIK\>"5f}
 UNIT1>SUUVPS,WIDE2-1: `0P8!_JK\>"5f}
 UNIT1>SUUVRU,WIDE2-1: `0P>!_JK\>"5Z}
 UNIT1>SUUVTP,WIDE2-1: `0PC!UIK\>"5W}
 UNIT1>SUUVVT,WIDE2-1: `0PK!_GK\>"5X}
 UNIT1>SUUVXT,WIDE2-1: `0PT!_EK\>"5Y}
 UNIT1>SUUVYX,WIDE2-1: `0P!_ =K\>"5X}
 UNIT1>SUUWRQ,WIDE2-1: `0Pj!_ =K\>"5W}
 UNIT1>SUUWTP,WIDE2-1: `0Pw!U=K\>"5T}
 UNIT1>SUUWUT,WIDE2-1: `0P□!U=K\>"5S}
 UNIT1>SUUXYT,WIDE2-1: `0R)!UNK\>"5P}
 UNIT1>SUUYPY,WIDE2-1: `0R-!_MK\>"5U}
 UNIT1>SUUYSR,WIDE2-1: `0R9!U:K\>"5P}
 UNIT1>SUUYUQ,WIDE2-1: `0RF!_ :K\>"5S}
 UNIT1>SUUYVU,WIDE2-1: `0RO!_ :K\>"5R}
 UNIT1>SUUYXW,WIDE2-1: `0R^!_ :K\>"5R}
 UNIT1>SVPPPQ,WIDE2-1: `0Rk!U:K\>"5U}
 UNIT1>SVPPQY,WIDE2-1: `0Ru!_ :K\>"5W}
 UNIT1>SVPPTQ,WIDE2-1: `0S !_ :K\>"5W}
 UNIT1>SVPPVP,WIDE2-1: `0S-!_8K\>"5T}
 UNIT1>SVPPWS,WIDE2-1: `0S8!_6K\>"5T}
 UNIT1>SVPPYT,WIDE2-1: `0SI!_6K\>"5T}
 UNIT1>SVPQQQ,WIDE2-1: `0SX!_2K\>"5V}
 UNIT1>SVPQRS,WIDE2-1: `0Sf!_K\>"5X}
 UNIT1>SVPQTP,WIDE2-1: `0S{!_*K\>"5[}
 UNIT1>SVPQUQ,WIDE2-1: `0T%!_*K\>"5]}
 UNIT1>SVPQXT,WIDE2-1: `0TN!_*K\>"5e}
 UNIT1>SVPRQQ,WIDE2-1: `0To!_*K\>"5h}
 UNIT1>SVPRRX,WIDE2-1: `0U !_ *K\>"5h}
 UNIT1>SVPRSY,WIDE2-1: `0U !_ +K\>"5i}
 UNIT1>SVPRUU,WIDE2-1: `0UA!_ +K\>"5j}
 UNIT1>SVPRWR,WIDE2-1: `0UW!_*K\>"5l}
 UNIT1>SVPRXS,WIDE2-1: `0Ud!_ +K\>"5m}
 UNIT1>SVPSXY,WIDE2-1: `0V}!_K\>"5h}
 UNIT1>SVPTPW,WIDE2-1: `0W !_K\>"5f}
 UNIT1>SVPTQY,WIDE2-1: `0W !_K\>"5d}
 UNIT1>SVPURX,WIDE2-1: `1Xk!_K\>"5N}
 UNIT1>SVPUUY,WIDE2-1: `1Y2!_K\>"5U}

UNIT1>SVPVQS,WIDE2-1:`1YM!\!K\>"58}
 UNIT1>SVPVRX,WIDE2-1:`1YF!3K\>"5,}
 UNIT1>SVPVUP,WIDE2-1:`1Y:!\4K\>"5'}
 UNIT1>SVPVWP,WIDE2-1:`1Y!/R4K\>"5#}
 UNIT1>SVPVXU,WIDE2-1:`1Y,!%\K\>"5"}
 UNIT1>SVPWVT,WIDE2-1:`1YY!_:K\>"5\$}
 UNIT1>SVPWYW,WIDE2-1:`1Yo!_:K\>"5.}
 UNIT1>SVPXQX,WIDE2-1:`1Y~!_:K\>"50}
 UNIT1>SVPXSW,WIDE2-1:`1Z(!_9K\>"50}
 UNIT1>SVPXUQ,WIDE2-1:`1Z1!_<K\>"51}
 UNIT1>SVPXWS,WIDE2-1:`1Z@!_:K\>"52}
 UNIT1>SVPYTQ,WIDE2-1:`1Zo!_8K\>"5'}
 UNIT1>SVPYUY,WIDE2-1:`1Z~!_4K\>"5%}
 UNIT1>SVQQPQ,WIDE2-1:`1"!_0K\>"4r}
 UNIT1>SVQQQX,WIDE2-1:`1\3!_0K\>"5"}
 UNIT1>SVQQQUP,WIDE2-1:`1\v!^wK\>"5%}
 UNIT1>SVQQQVP,WIDE2-1:`1j/!^wK\>"5%}
 UNIT1>SVQQVU,WIDE2-1:`1]A!^wK\>"5%}
 UNIT1>SVQQWS,WIDE2-1:`1][!^wK\>"5"}
 UNIT1>SVQQXS,WIDE2-1:`1]x!^wK\>"4{}
 UNIT1>SVQQXX,WIDE2-1:`1^&!^wK\>"4{}
 UNIT1>SVQQYV,WIDE2-1:`1^?!^wK\>"4{}
 UNIT1>SVQRQS,WIDE2-1:`1_&!^iK\>"5"}
 UNIT1>SVQRQV,WIDE2-1:`1_F!hhK\>"5#}

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APPENDIX D. BEELINE

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